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A practical manual for aquatic biomass estimation

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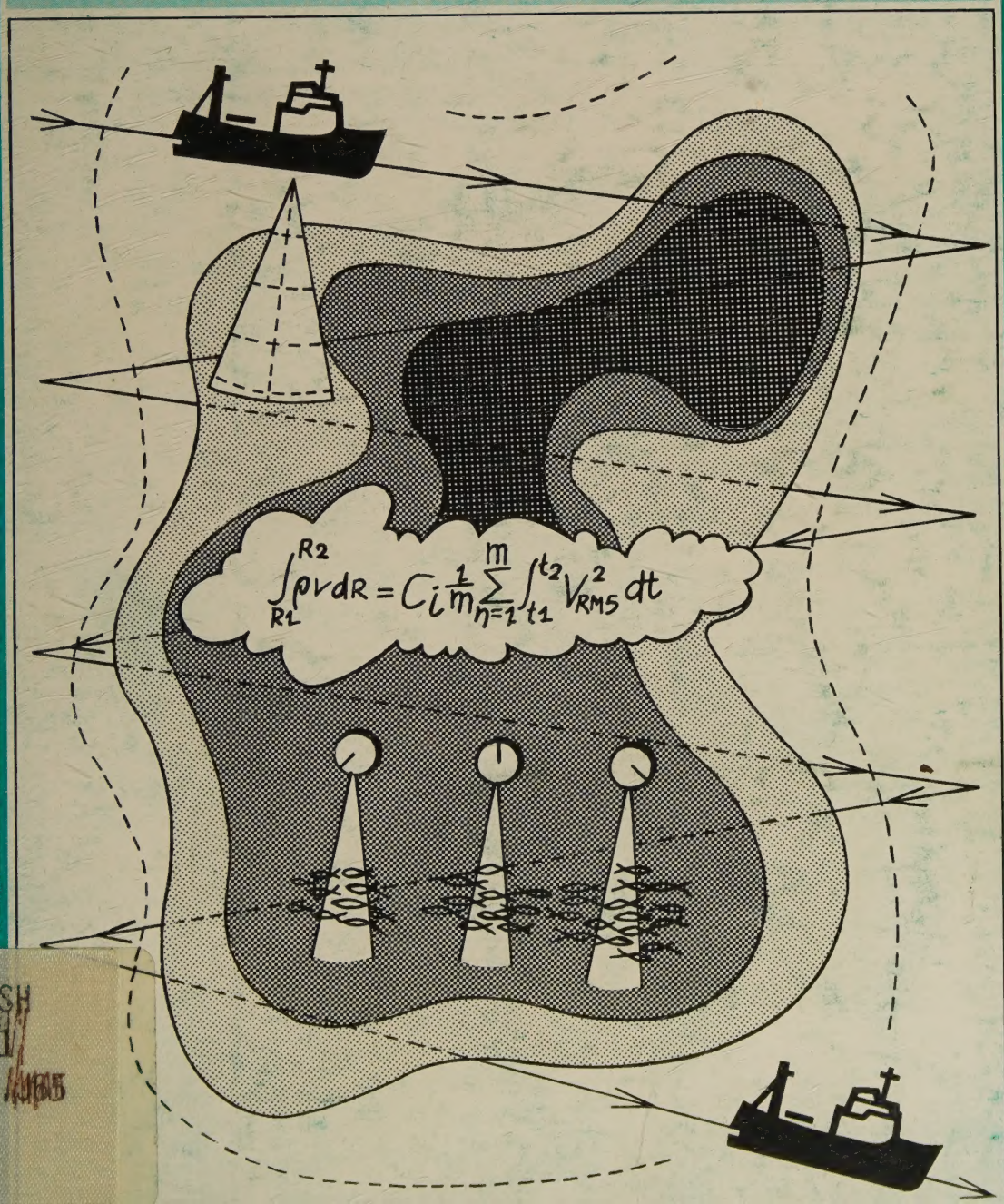

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Fisheries acoustics

A practical manual for aquatic biomass estimation

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Rome, 1983

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PREPARATION OF THIS MANUAL

Acoustic surveys have developed from the estimation of relative abundance of fish to the measurement of their absoluate abundance in recent years. If the results of acoustic surveys are to fall within certain prescribed limits of accuracy necessary to meet their various objectives many factors must be taken into account. In order to ascertain these factors and their relative importance, expertise from the physical, mathematical and biological disciplines is required, plus practical experience with the available equipment and the techniques for its use to survey different fish stocks in many parts of the world.

This manual has been produced because the existing publications deal separately with the many aspects of acoustic surveys. The intention here is to present the whole subject with emphasis on practical application and the problems usually encountered.

It was in Peru during 1980 that the first stage of preparation began in the closing weeks of the project run by the FAO/Norway Regional Acoustics Research Centre in Lima. However, this coincided with the announcement of completely new equipments thus rendering obsolete part of the material collected. Much of the emphasis has been removed and a full revision of the manual has since been supported by the FAO/CIDA Indonesian Fisheries Development Project.

The use of brand names is unavoidable in this kind of document. Information has been included on all brands of commercially available acoustic equipment known to us at the time of preparation.

It will be evident to readers from the list of references and recommended reading, that the authors have drawn on the published work of many people.

Special thanks in acknowledgement of their comments and criticism is due to the following: H. Bodholt, J. Burczynski, R. Brede, D.H. Cushing, J.E. Ehrenberg, K.G. Foote, M. Lamboeuf, O.A. Mathisen, B.J. Robinson and R. Shotton. The authors especially thank S.C. Venema of the Fishery Resources and Environment Division of FAO without whose advice, support and encouragement this manual could not have been completed.

This manual was typed in Lowestoft by Mrs. Doreen Wadland and proof-read by Mrs. P. Mitson. At FAO the references were checked by Ms. Gloria Soave and typed by Ms. Doris Dearing.

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ABSTRACT

The manual begins with a presentation of key physical principles used in fisheries acoustics and continues with a general description of the necessary equipment and its functions. An explanation is given of the acoustic equations followed by the acoustic properties of fish when occurring singly or in schools. Acoustic survey concepts are discussed prior to a description of calibration methods used to determine the electronic and acoustic parameters of the equipment. Use of the equipment in a systematic manner at sea leads on to the sources of error that can arise and explains how these may be removed or minimised. Finally methods are given for the collection and presentation of data in various forms, together with different ways in which to improve results by the use of statistics.

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1. INTRODUCTION

1.1 Development of Acoustic Methods in Fisheries

An acoustic method for the detection of fish was first reported in the scientific literature in 1929. Continuous waves (CW) at a frequency of 200 kHz were directed across ponds containing goldfish. As the number of fish intercepted by the acoustic beam changed, so the amplitude of the signal recorded on an oscillograph varied. This work was published by Kimura (1929) in the Journal of the Imperial Fisheries Institute of Japan.

A most important development was the paper recording echo-sounder by Wood et al, (1935), which was used for surveys of cod (Sund, 1935) and is still widely employed. A flashing light echo-sounder made by the Marconi Company was also used at this time for detecting herring shoals but reported later (Balls, 1946).

Rapid advances in the application of echo-sounders to fishing occurred after World War II and they were also used for the estimation of relative fish abundance. For this purpose a technique of counting the numbers of millimetres of fish echo trace from the paper record was used, Cushing (1952).

For the next stage of development, attempts were made to count and size fish from their echoes (Mitson and Wood, 1962 and Cushing, 1964), but for various reasons these met with limited success. It was mainly the use of an electronic integrator to process the fish echoes that marked the beginning of quantitative assessment of fish stocks by acoustic methods as we know it today (Dragesund and Olsen, 1965).

The development of these methods for fish stock estimation has progressed steadily (Middtun and Nakken, 1971) during a period when major advances in electronics technology have taken place. As a result of these advances it is possible to process signals derived from fish echoes, fast and accurately, with equipment which is both reliable and stable. Attention is being increasingly directed toward aspects of fish behaviour such as their orientation, density and distribution, all factors which can bias the results of an acoustic survey. Thought is also being given to the planning of surveys and the statistical manipulation of data to give the best possible measurement of abundance.

In putting together this manual the authors have drawn on the experience and writings of many people in an attempt to provide a suitable amount of technical background and practical 'know-how'. An outline of the contents is given next.

1.2 Contents of this Manual: Its aim and scope

Many FAO fisheries development projects included as one of their objectives the development of a national capability to independently accomplish programmes of fisheries resource studies, based on modern acoustic survey equipment and techniques. Transfer of expertise through direct training of project counterparts is an important activity towards this end and the preparation of this Manual represents an additional effort to prepare and train scientific and technical counterpart personnel for their future tasks.

Because there is no single traditional academic base for the mixture of knowledge and skills required by the profession, a manual such as this is thought to provide a

useful additional resource for acoustic practitioners, especially at the earlier stages of experience. Emphasis has been placed on the practical aspects of the topics treated, assuming only a limited knowledge of the reader in mathematics and physics. An attempt has also been made to cover the essential ground in a coordinated manner with respect to the three previously issued FAO Manuals and technical papers on the subject, by Forbes and Nakken (1972); Burczynski Revision 1 (1982) and Bazigos (1981), keeping the overlap to a necessary minimum to maintain continuity. Hence, sections may not be fully comprehensive because they are intended to lead to some further study on each topic, using the recommended literature in Appendix 3.

The contents of the present Manual have been arranged to introduce the reader to some elementary theory related to the physical background and outlines the principles of the necessary equipment before deriving the working formulae. It then deals with the acoustic properties of fish in some detail before considering the general concepts behind acoustic estimates of biomass.

There is a section on acoustic and electronic calibration, after which the planning of work and shipboard procedures are presented in a practical manner. Probably the largest chapter (9) is that dealing with possible sources of error in the estimates and how these may be combated. The final chapter (10) is concerned with analysis of data collected during fish abundance surveys.

2. KEY PHYSICAL QUANTITIES

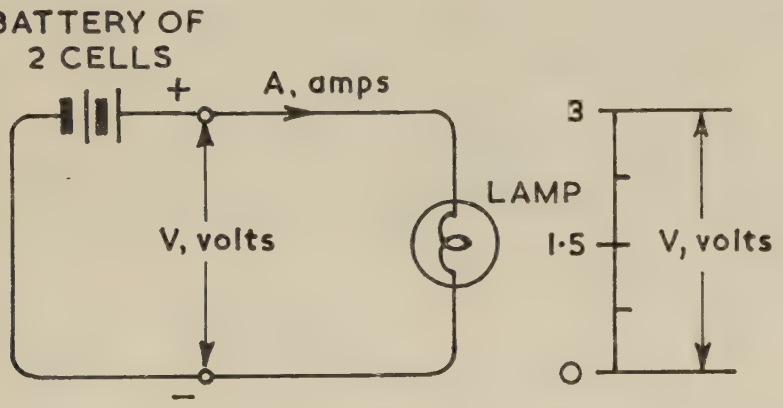
For a proper understanding of the acoustics used in fisheries it is necessary to have some knowledge of simple electricity, electromagnetic waves and acoustic waves.

An important purpose of this chapter is to explain the term power, a matter which is crucial to electrical and acoustic measurements. Power is defined as the amount of energy flow per unit time, or simply as the 'work done' in a given time. It is a well known law of physics that energy can neither be created nor destroyed, but is converted from one form to another. The process of conversion from the form we have, for example electrical energy, to the form we want, perhaps acoustic, cannot be 100% efficient and consequently some may turn into an unwanted form, often heat. It is vital that measurements in fisheries acoustics are based on the true power of the signals and to explain this fully we first consider direct electrical current, then alternating current which is in turn related to acoustic factors in section 2.4.

2.1 Direct Electrical Current (DC)

Electrical energy can be stored in many ways but the simplest for the present purpose is the chemical form in a battery of cells from which direct current (DC) is obtained (current means the flow of electrons in a circuit). The laws governing electrical matters are most easily understood by the application of DC to simple electrical circuits.

Figure 1.



A battery presents a steady potential difference (pd), or voltage (V) across its terminals Fig. 1, and if, for example, a lamp is connected to the terminals a direct current will flow through both circuit and battery. Work is being done because electrical energy is being converted to light as the current flows through the lamp filament. The amount of energy changed from electricity to light when measured over a period of time is known as the power (W, watts) dissipated and this is controlled by the voltage (V) of the battery and the amount of current (A) which is flowing. In fact a small proportion of the energy is 'wasted' in the form of heat but this is not important to the present explanation.

Power is the product of V, volts and A, amps

Power, (W, watts) = V x A ..... (1)

Current flow A is directly proportional to V but is controlled by the resistance R (ohms) of the lamp filament.

$A = V/R$ ..... (2)

If we substitute eqn 2 for A in eqn 1

$$\text{Power} = V \times V/R = V^2/R \text{ Watts} \quad \ldots\ldots\ldots\ldots (3)$$

The relationship of power to work and energy is given in Appendix I under derived units. It is particularly important to remember that power is proportional to voltage squared.

Sources of direct current are used to provide power for the operation of electronic devices and systems but have no other useful function. Direct current can be produced from rotating machines (generators), but the natural output of any such machine is an alternating current wave, the description of which is given in the next section.

2.2 Alternating Electrical Current (AC)

Figure 2

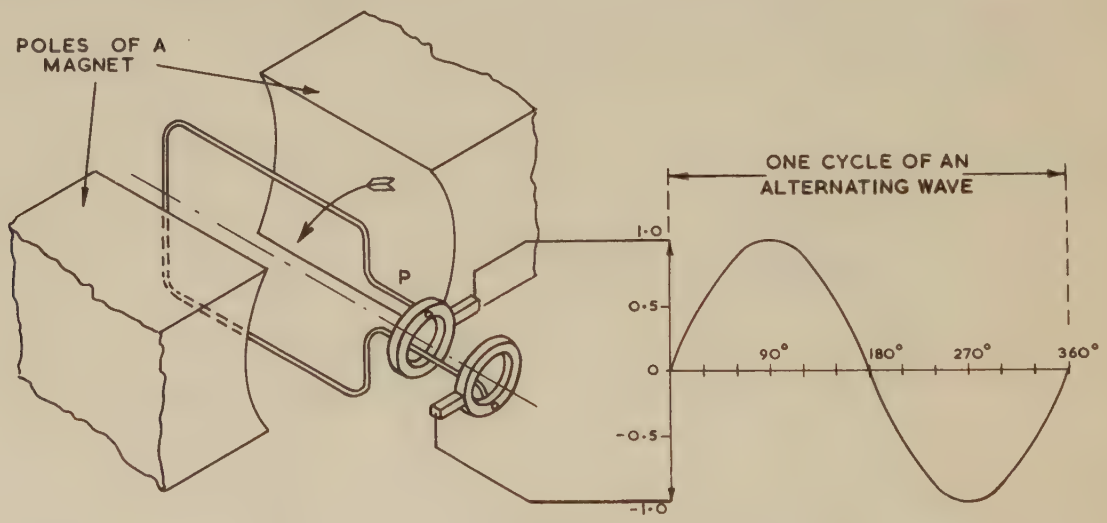
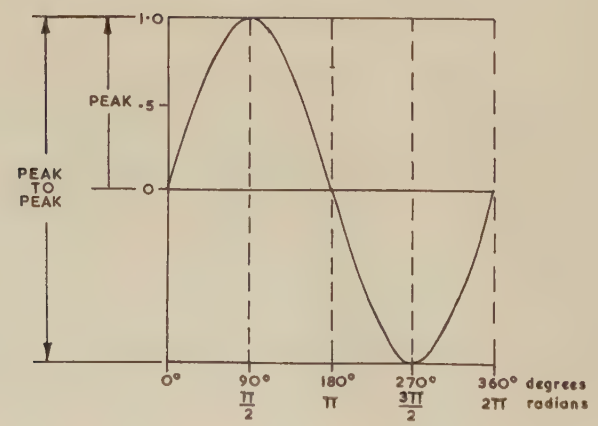


Figure 3

(a) (b)



Electronic and acoustic systems which propagate and receive energy do so by the use of electromagnetic or acoustic waves. The characteristic properties of waves are the same in air, solids, or water. A wave is defined as a progressive disturbance in any of these media. It is formed by the propagation of alternating tensions and pressures, without permanently displacing the medium itself.

An alternating electrical wave can be produced by the rotation of a rectangular loop of wire at a constant speed in a magnetic field. This is shown diagrammatically in Figure 2(a). It can be demonstrated by the laws of electromagnetic induction that the current in the loop will vary according to the angle of the loop relative to the magnetic field. If terminal P is taken as a reference, rotating from 0° to 360°, the direction of the current and its amplitude can be plotted against the angle of rotation as in Figure 2(b). For convenience, intervals of 30° are used.

It is clearly seen that the wave is going in one direction for the first 180°, then it goes through zero and reverses direction (polarity) for the next 180°. The maximum values in each direction occur 90° after passing the zeroes. In its pure (undistorted) state, the amplitude and other characteristics of a sinewave can be easily measured but special care must be taken to avoid confusion. For example it is necessary to be absolutely clear in stating that values are from zero to maximum in one direction (peak) or, if quoting from the extreme peak of one direction to the extreme peak in the other direction (peak-to-peak), see Figure 3.

Although peak, or peak-to-peak values must be recorded, this is simply because they are the recognisable points of a sinewave, it is necessary to convert them before making any calculations of power. The reason is that we are concerned with the actual amount of energy involved, but, whereas with DC this could be obtained by the product of voltage V and current A, in the present case these quantities are continuously alternating so will not yield a correct answer (the average value in fact is zero). We must seek the value of alternating current which does the same amount of 'work' as would a DC current if flowing in the same circuit.

2.3 Root-Mean-Square (rms) Values

We have already seen in 2.1 how power is calculated in a DC circuit,

eqn.1 $W = V \times A$

and transposing eqn. 2 $V = AR$

substituting for V in eqn.1 $W = A^2R$ ..... (4)

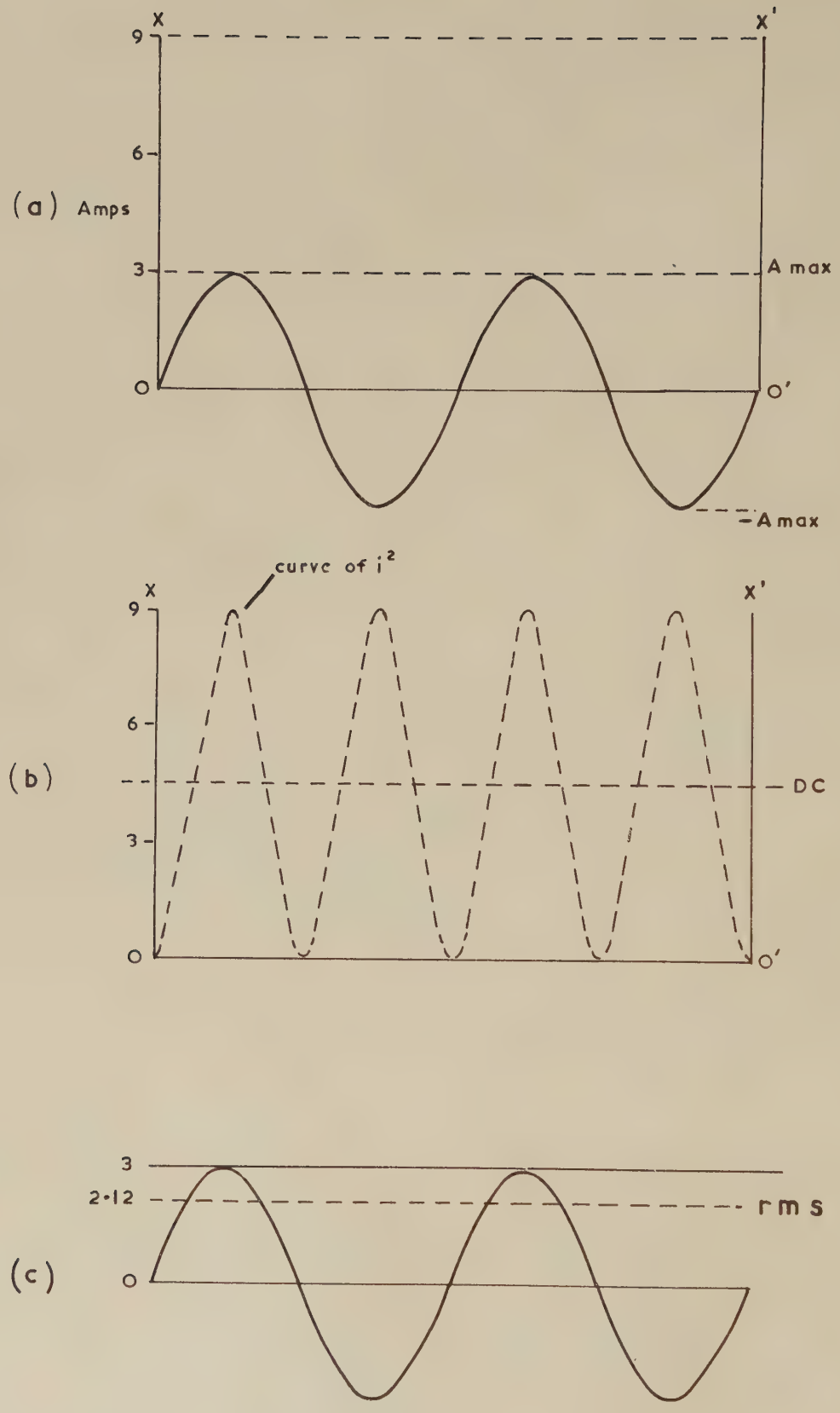
which is a more convenient form for our present purpose.

If a DC of 3A flows through a resistor of 1 ohm the power dissipated is

$$W = 3^2 \times 1 = 9W$$

and this is represented in Figure 4(a) by the area OX by XX'.
On the same figure there is a sinewave of 3A maximum.

Figure 4



A sinewave can be defined as $A_{max} \sin \omega t$

where A_{max} is the peak amplitude in each direction of the waveform.

$\omega t = 2\pi$ or 360° at the end of one cycle, see Figure 3.

The instantaneous value of current is $i = A_{max} \sin \omega t$.

If this is flowing in a circuit of one ohm resistance, the instantaneous rate of power dissipation is

$$i^2 \times 1 \text{ Watts} = i^2 \text{Watts}.$$

Thus we can square the instantaneous values of the sinewave and, using our example having a maximum of 3A this produces the dotted curve in Figure 4(b). It is easy to see, or to calculate, that the area under the dotted curve is half that of the area OX by XX', that is to say, when the DC has an amplitude equal to the maximum AC the power dissipated by the AC is half of that dissipated by the DC.

Still using the values in Figure 4 it is possible to determine the proportion of the AC_{max} value which gives the same power dissipation as DC.

The DC to give the same power dissipation as the maximum AC is seen from Figure 4(b) to be 9/2 = 4.5A.

So $4.5 = A_{DC}^2$

Then $A_{DC} = (4.5)^{\frac{1}{2}} = (9/2)^{\frac{1}{2}} = 3/2^{\frac{1}{2}}$ ie. 3 divided by the square root of 2.

but the AC_{max} value is 3, so we can say $1/2^{\frac{1}{2}}$ times 3.

$$A_{DC} = 1/2^{\frac{1}{2}} A_{max} = 0.707 A_{max} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Summing up we can say that the rms value of a voltage, or current, is the square root of the mean (average) of all the instantaneous amounts of energy squared, rms is also known as the effective, or virtual value of AC.

To find the rms value, multiply the peak value by 0.707.

To find the rms value from a peak-to-peak figure, first divide by two, then multiply by 0.707. Electrical powers and voltages can be cumbersome to manipulate and calculate so it is normal practice to convert these to a more convenient form. This is the decibel (dB) which is described in section 2.5.

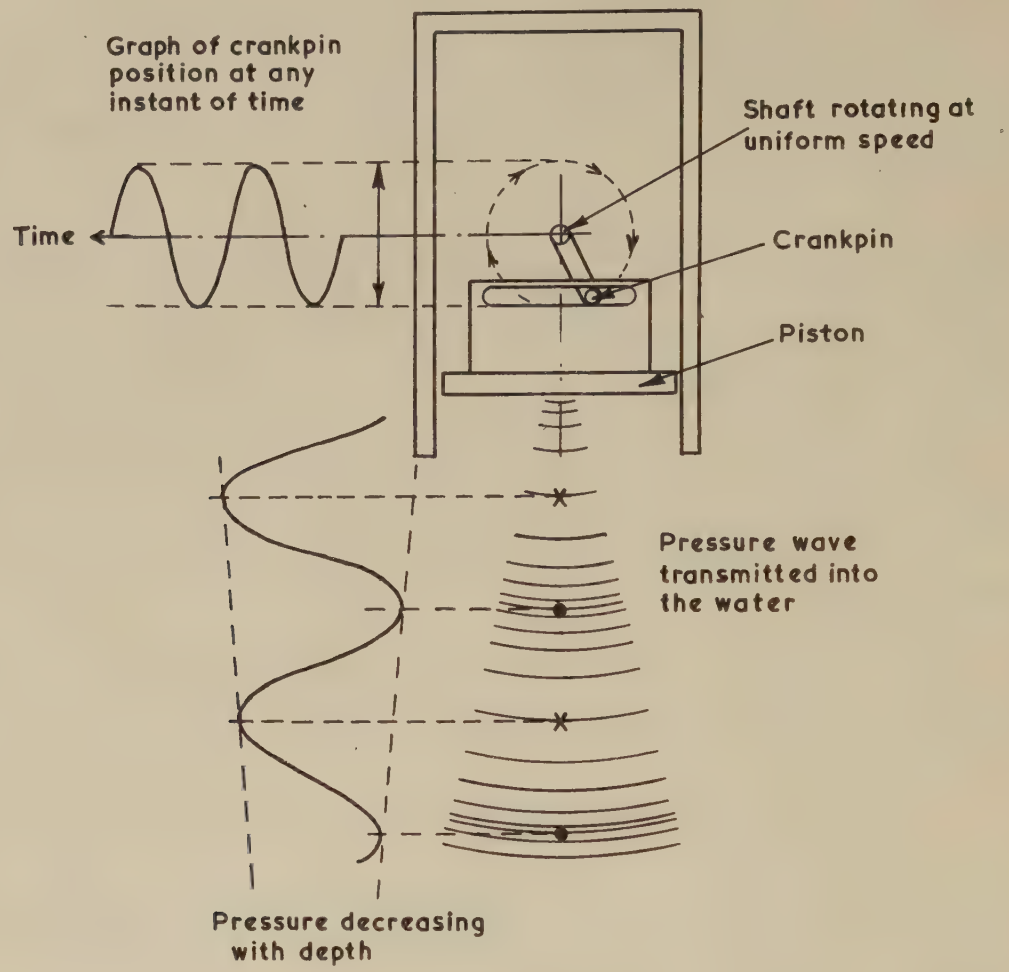
2.4 Acoustic Pressure and Intensity

2.4.1 Pressure

Pressure is most easily thought of as a mechanical force. It can be generated by the movement of a piston as shown in Figure 5. If the constant speed rotation of the shaft is transmitted by the crankpin to the piston in the manner illustrated, the result is a sinusoidal motion. This sets up an acoustic pressure wave of sinusoidal oscillations in the water with regions of compression and rarefaction relative to the mean pressure, see Figure 5. In acoustics we are concerned with sinewaves in a similar way to the electrical sinewaves discussed in section 2.2, i.e. the 'work done' or the power used is the rms value. Any practical measurement of acoustic waves is made by observing the electrical output signal (sinewaves) of a pressure sensitive device (transducer). In other words the sinusoidal pressure wave is converted into an

equivalent electrical sinewave from which the acoustic properties can be determined.

Figure 5.



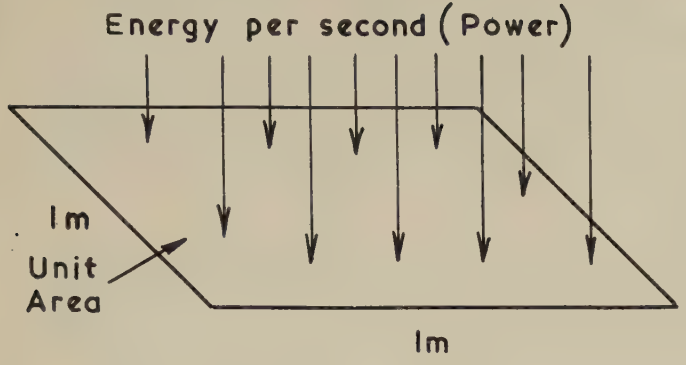
Acoustic waves are a form of energy which can be propagated through a medium having distributed mass and elasticity, such as water. At any point where these waves are found in the water, energy is present as a change in the normal state of stress and strain. Energy causes force to be exerted and the oscillations of the particles comprising the medium are therefore transmitted from point to point in the water at a speed depending on the factors given in section 2.6.1.

The relationship between pressure, particle velocity and the quantity ρc is similar to that which exists in electricity between voltage, current and resistance (impedance), sections 2.1 and 2.2. Acoustic impedance ρc is defined in terms of the constants of the medium, ρ being the density in kg/m^3 and c the speed of acoustic waves in m/s, therefore $\rho c = kg/m^3 \times m/s = kg/m^2.s$. The unit of acoustic impedance is known as the Rayl (after Lord Rayleigh) and for seawater it is approximately 1.54×10^6 Rayls.

Pressure is measured in micropascals (μPa). One μPa is equal to 10^{-6} Newtons/m^2. Micropascals are used as the standard reference unit because the Pascal (1 Newton/m^2) is only a factor of 10 different to the previous standard, the μbar which can be seen in old textbooks. To convert any figures given in $dB/1\mu b$ it is necessary to add 100, e.g. 120 $dB/1\mu b$ = 220 $dB/1\mu Pa$ and -100 $dB/1V/1\mu b$ = -200 $dB/1V/1\mu Pa$. See Appendix I and section 2.5.

2.4.2 Intensity

Figure 6



Acoustic intensity (I) is defined as the amount of energy per second (power), passing through unit area normal to the direction in which the acoustic wave is propagated. This concept is illustrated in Figure 6.

In section 2.4.1 it was stated that pressure, particle velocity and ρc are analogous to the electrical quantities of voltage, current and resistance, respectively. Acoustic intensity is analogous to electrical power on the basis of the amount of energy and the time it flows or is used. So equation 3 can be presented in acoustic terms as

$$\text{Intensity } (I) = p^2/\rho c \qquad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

i.e. the intensity is proportional to the pressure squared divided by the acoustic impedance.

The intensity of an acoustic wave is referred to a plane wave of rms pressure equal to 1μPa at a distance of 1 m from the source. For the purpose of fisheries acoustics a plane wave can be described as one which exhibits no significant curvature of its wavefront over the length or extent of a target.

2.5 Decibels

A decibel (dB) is one tenth of a Bel, the unit named after Alexander Graham Bell, a famous inventor. It was first used in connection with telephone transmission lines (Martin, 1929) but is now common to all branches of electronics and acoustics.

The decibel is NOT a unit of measured quantity such as metres, kilogrammes or seconds. It is the logarithm to base 10 of a ratio, giving the relationship between quantities. In electronics there are often very large differences, or changes, in the power or voltage between one part of a system and another. In underwater acoustics big differences occur in intensity and pressure due to propagation losses, for example. By converting these changes to decibels using logarithms it is possible to simplify figures and calculations of gains or losses. Since the decibel is based on logarithms, multiplication and division are converted into addition and subtraction.

2.5.1 Power and Intensity Ratios

Electrical power, (W, watts) is analogous to acoustic intensity (I) section 2.4, and the same factor $10 \log_{10}$ is used for both, hereafter in the manual 10 log will be used. The decibel notation for a power W is

$N = 10 \log W/Wo$ dB where Wo is the chosen reference power

similarly for an intensity I

$$N = 10 \log I/Io \text{ dB} \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

where Io is the chosen reference intensity.

The logarithmic ratio between two quantities one of which is twice the size of the other could be log 2/1 or log 1/2 depending on the reference. Taking logs, the ratios become +0.3010 and -0.3010 respectively. Changing these to decibels in the case of power or intensity the ratios are multiplied by 10

10 log 2/1 = +3 dB and 10 log 1/2 = -3 dB

In other words +3 dB indicates that the quantity is twice as large as the reference, whilst -3 dB indicates that it is only half the reference. Similarly

10 log 10/1 = +10 dB and 10 log 1/10 = -10 dB

10 log 100/1 = +20 dB " 10 log 1/100 = -20 dB.

Table 1 shows the number of decibels equivalent to power and intensity ratios. A ratio relating to a decibel number not in the table can be found by

ratio = Antilog (ndB/10) or $10^{n/10}$

alternatively numbers can be selected from the table of dB's to make up the number to be converted, e.g. 75.5dB is 70 + 3 + 2 + 0.5 and the corresponding ratios are 10^7, 2, 1.58 and 1.12, which when multiplied together = 2 x 1.58 x 1.12 x 10^7 = 3.539 x 10^7.
Table 1 shows the number of decibels equivalent to power and intensity ratios.

Table 1

Number of Decibels	Power (W) and Intensity (I) Ratio	
	+dB	-dB
0.1	1.02	0.98
0.5	1.12	0.89
1	1.26	0.79
2	1.58	0.63
3	2.00	0.5
6	3.98	0.25
10	10.00	0.10
20	10^2	0.01
30	10^3	10^{-3}
40	10^4	10^{-4}
50	10^5	10^{-5}
60	10^6	10^{-6}
70	10^7	10^{-7}
80	10^8	10^{-8}
90	10^9	10^{-9}
100	10^{10}	10^{-10}

2.5.2 Voltage and Pressure Ratios

In section 2.1 it was shown that power is proportional to voltage squared; there is the same relationship between acoustic intensity and pressure (section 2.4).

The decibel notation is therefore

$$10 \log(V^2/R)/(Vo^2/R) = 20 \log V/Vo \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

and $$10 \log (p^2/\rho c)/(p_0^2/\rho c) = 20 \log p/p_0 \quad \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

where Vo and p_0 are the respective reference quantities and ρc is the specific acoustic resistance of the water (analogous to resistance in the electrical circuit, (ρ is the density in kg/m^3 and c = acoustic wave speed in m/s).

From the example in the previous section it was shown that the logarithmic ratio between two quantities of power or intensity, one of which is twice the size of the other, is +3.010 and -3.010 depending on which is taken as the reference quantity.

Changing these to decibels of <u>voltage</u> or <u>pressure</u>, the logarithms of the ratios must be multiplied by 20

$20 \log 2/1 = +6dB$ and $20 \log 1/2 = -6dB$.

Table 2 shows the number of decibels equivalent to voltage and pressure ratios.

Table 2.

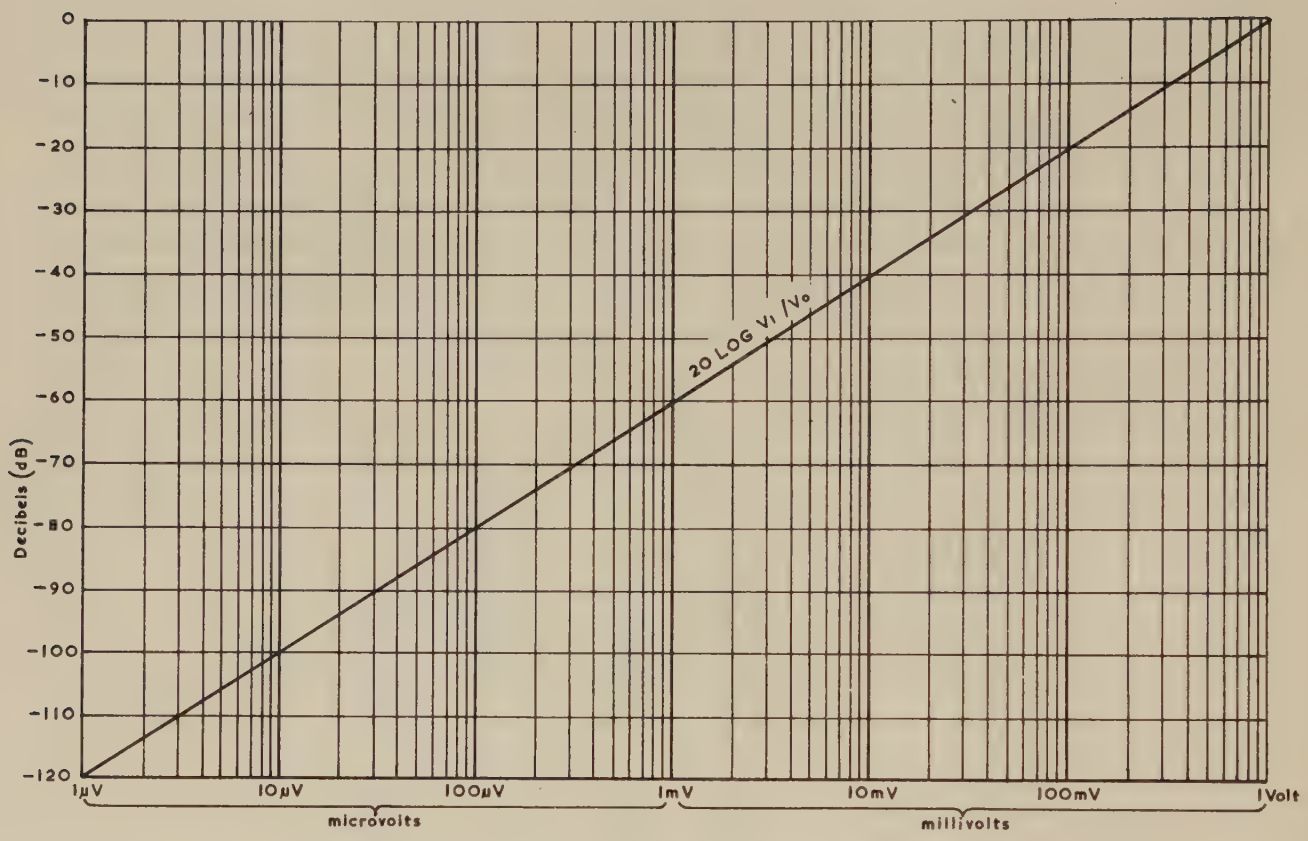
Number of decibels	Voltage and Pressure Ratio	
	+dB	-dB
0.1	1.01	0.99
0.5	1.06	0.98
1	1.122	0.84
2	1.26	0.79
3	1.41	0.71
6	2.0	0.50
10	3.16	0.316
20	10.00	0.1
30	31.62	0.0316
40	10^2	10^{-2}
50	316.0	0.00316
60	10^3	10^{-3}
70	3162	3.162×10^{-3}
80	10^4	10^{-4}
90	31622	3.162×10^{-4}
100	10^5	10^{-5}

The dB reference for voltage is often 1 Volt, in which case a measurement of less than 1 Volt must be -ndB/1Volt.

10^{-5} Volts = 20 x -5 = -100 dB relative to 1 Volt

$1\mu V = 10^{-6}$ Volts = 20 x -6 = -120 dB relative to 1 Volt.

Figure 7 shows this relationship over a useful range of voltage.

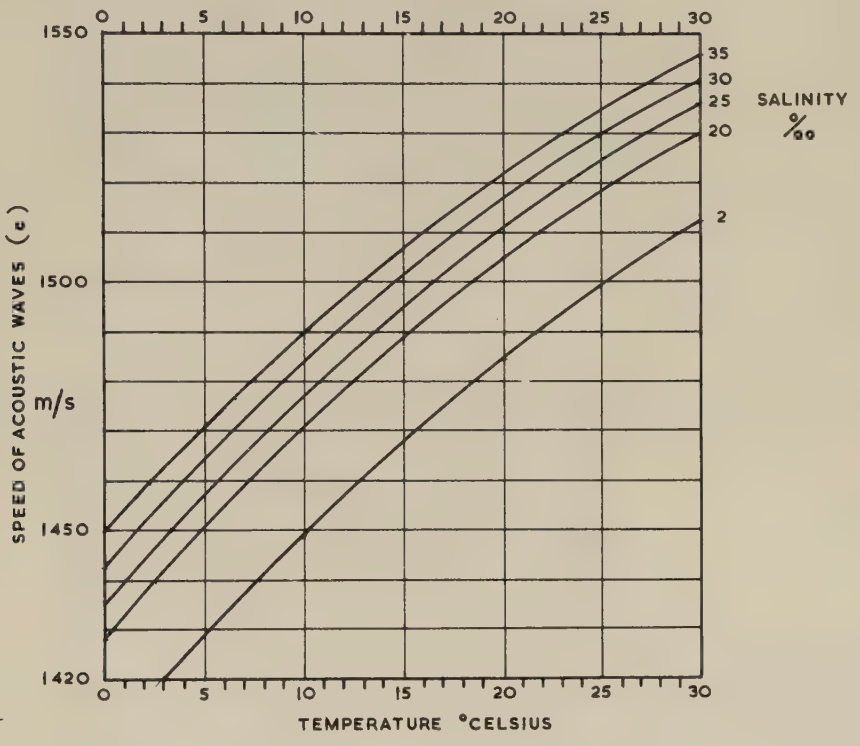


2.6 Speed and Absorption of Acoustic Waves

The speed of acoustic waves in the sea is denoted by the symbol c and is measured in metres/second (m/s). It is a variable dependent on the temperature, salinity and depth of the water, although the depth factor is not significant for fisheries acoustics.

Depth can only be measured correctly if the acoustic wave speed is known for the area being surveyed. Figure 8 shows the variation of speed against temperature and for a number of salinities. It is evident from this figure that changes of the order of 2½% might occur between summer and winter but this is usually considered to be insufficient to justify correction to the timing system of the echo-sounder.

Figure 8.



The speed of an acoustic wave is $c = f\lambda$ ..... (10)

where c is in m/s f is in Hz

λ is the wavelength (see section 2.7) in metres.

The frequency f is fixed in an echo-sounder but the wavelength varies with the speed of the waves

$\lambda = c/f$ ..... (11)

assuming a speed of 1500 m/s (the most commonly used figure) and a frequency of 38,000 Hz ie 38 kHz, the wavelength is

$\lambda = 1500/38000 = 0.0395$ m or 39.5 mm

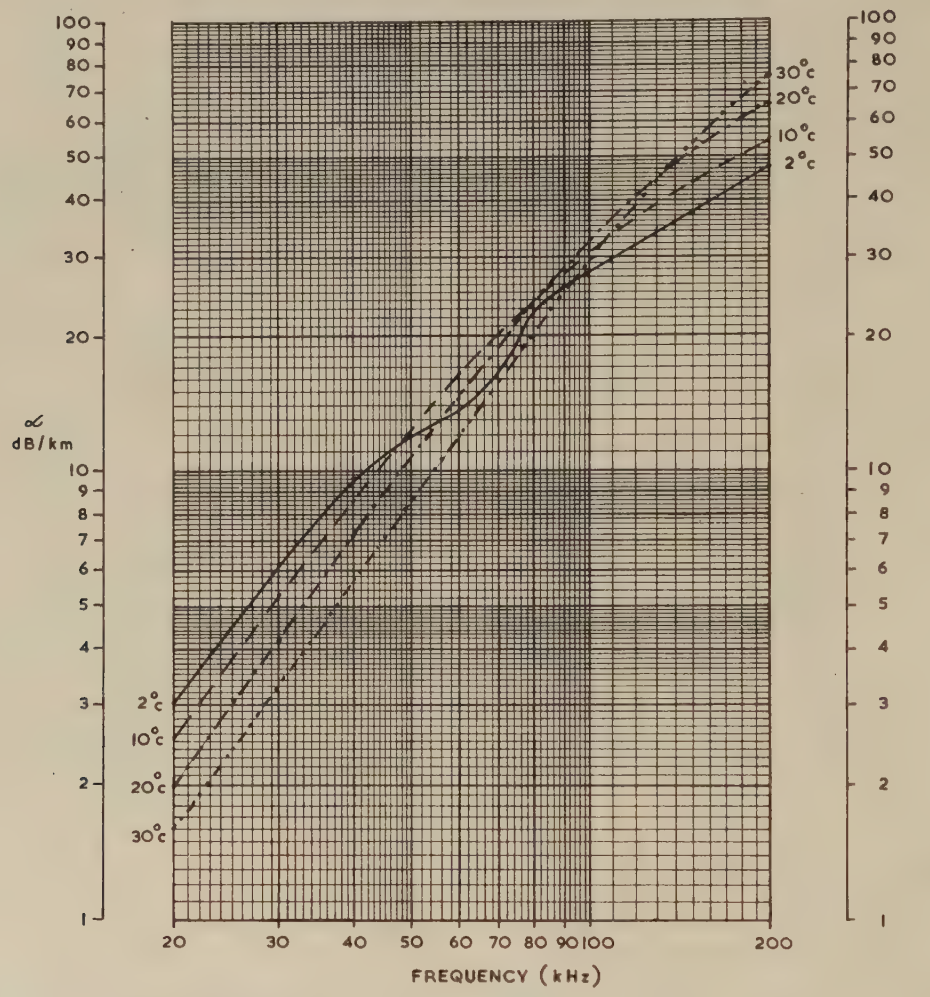
If the speed increases by 20 m/s to 1520 m/s the wavelength increases, by 0.5 mm, to 40 mm, not a significant change. Although thermoclines (layers of water in which the temperature changes abruptly with depth) occur frequently due to a variety of causes, the consequent change in speed of acoustic waves is unimportant for echo-sounding purposes i.e. the difference in acoustic impedance ρc is too small to be detected.

2.6.1 Absorption of Acoustic Waves

As acoustic waves travel through water, some of the energy is absorbed by chemical processes. The proportion of energy which is converted must be regarded as an acoustic loss and taken into account when calculating results. The loss is linear with distance, ie for each metre travelled a constant fraction of acoustic energy is lost.

Absorption is denoted by the symbol α and is expressed in decibels per kilometre (dB/km), it increases with frequency as shown in Figure 9.

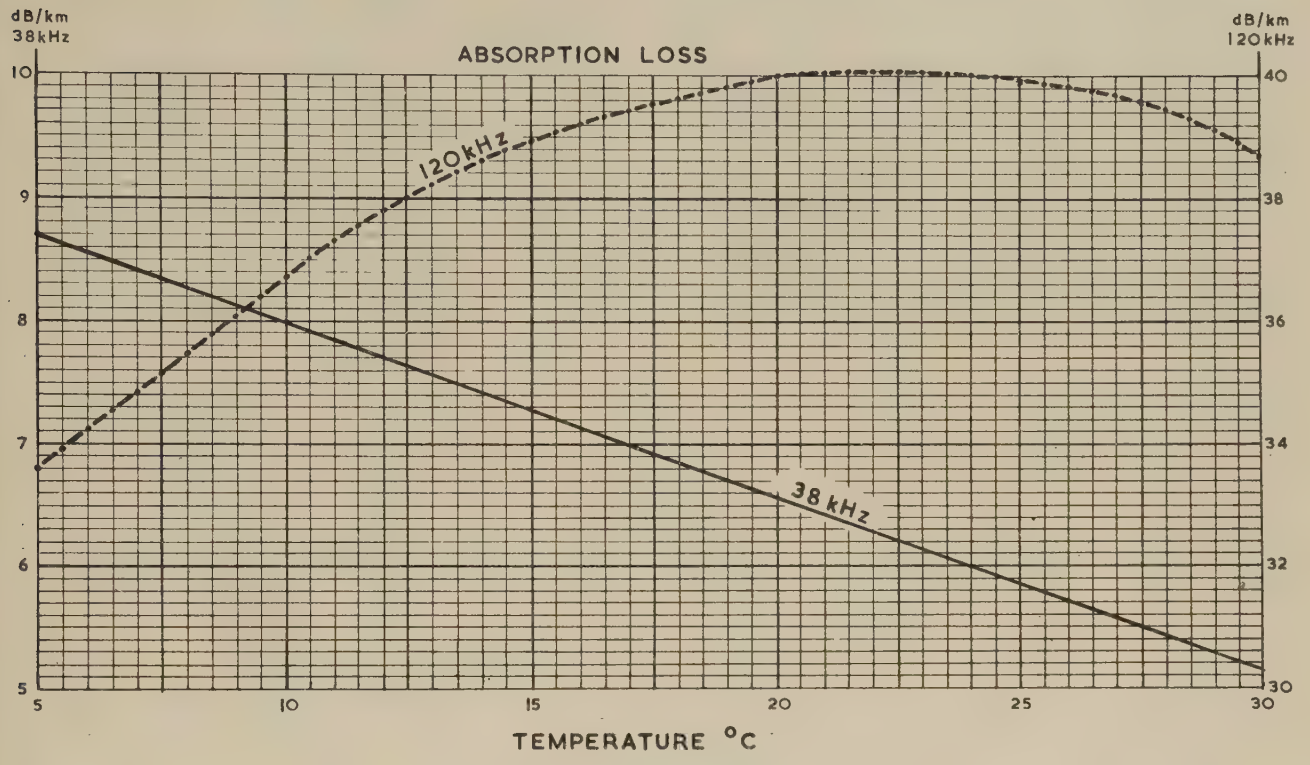
Figure 9.



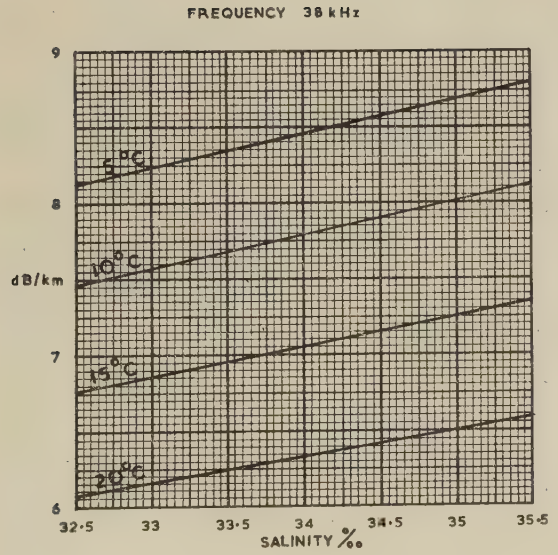
There is a marked temperature dependence but this exhibits different characteristics; at the low end of the frequency scale below 70 kHz where there is a negative gradient, an increase in temperature gives a reduced α. At 120 kHz the gradient is first positive, then negative as in Figure 10(a). These figures are calculated from a formula derived by Fisher and Simmons (1977) after a series of experiments and it is believed to give the most accurate results currently available for fisheries acoustic work. Further research is needed to confirm the validity of the results for all conditions of temperature and salinity likely to be encountered in practical surveys. Nevertheless it is recommended that the graphs in Figures 9 and 10(a)(b)(c) be used to select the value of α for surveys until further results are forthcoming. Variation of

the values of absorption for changes in salinity at commonly used acoustic survey frequencies are plotted in Figure 10(b)(c).

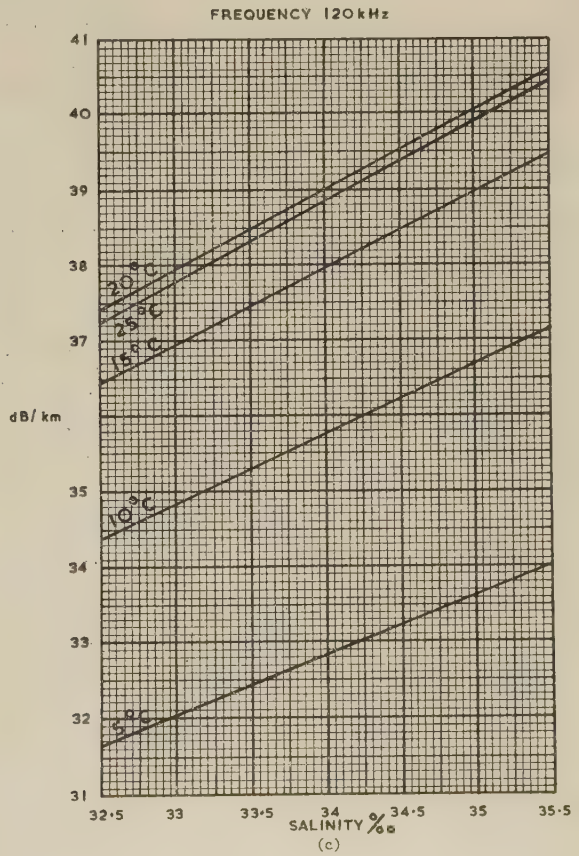
Figure 10



(a)



(b)



(c)

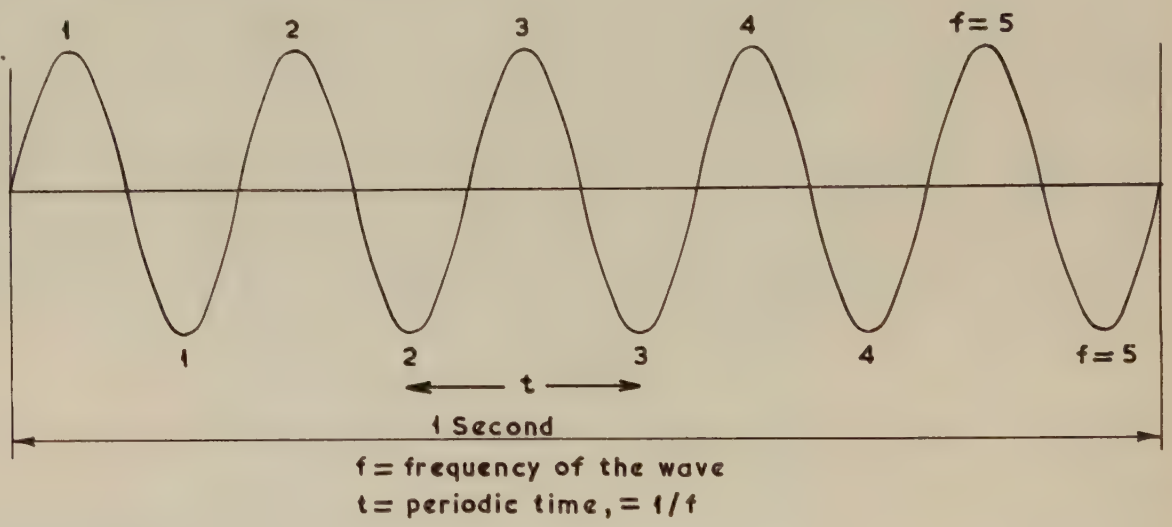
2.7 Frequency and Wavelength

The frequency of a sinewave is defined as the number of peaks of one polarity which occur in one second. Frequency is measured in terms of cycles, ie the number of complete sinewave cycles in one second, but the unit of frequency is now Hertz (Hz) after the physicist of that name. Thus in Figure 11 the sinewave shown has a frequency of 5 Hz.

The term ω was used without explanation in section 2.3. It denotes the angular velocity of a wave i.e. the rate at which a particle moves through the cycle, and is equal to $2\pi f$. For the frequency of 5 Hz the angular velocity is 31.416 radians/second.

Periodic time (t) is the time taken for completion of a cycle, or for adjacent peaks to occur, see also Figure 11. The sinewave in section 2.3 was defined as $A_{max} \sin \omega t$ and the completion of a cycle when $\omega t = 2\pi$, therefore $t = 2\pi/2\pi f = 1/f$ so the periodic time of a 5 Hz wave is 1/5 second.

Figure 11.



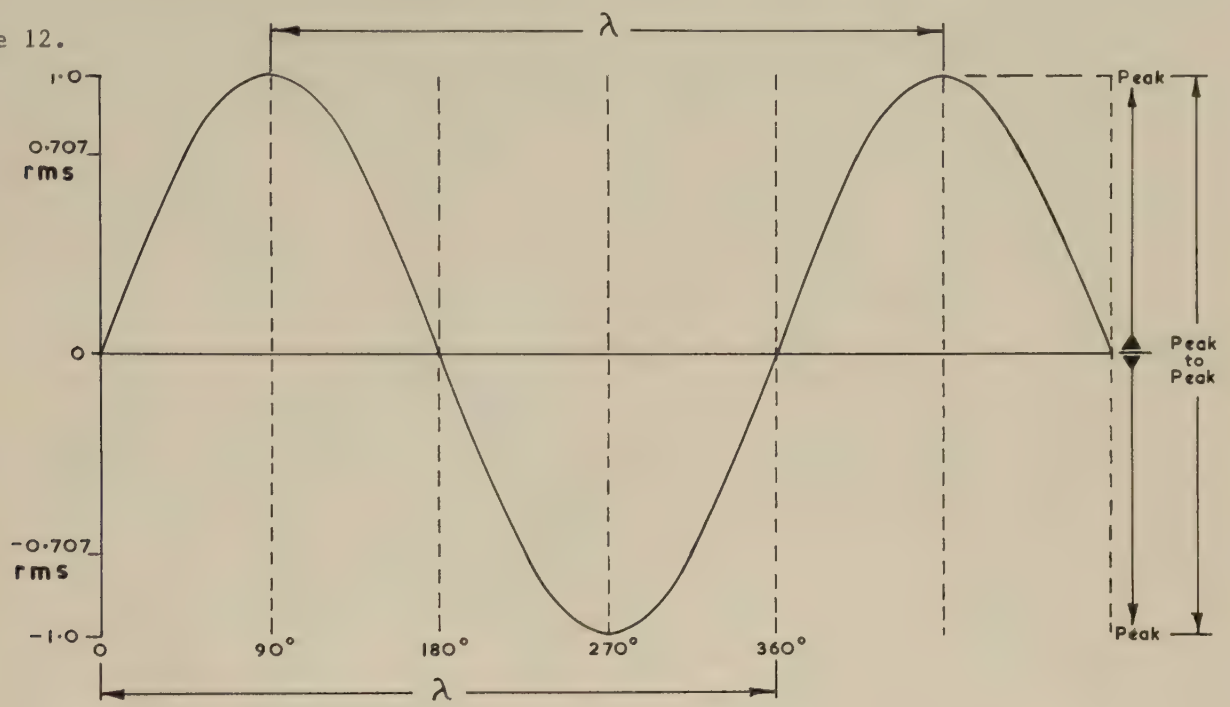
In fisheries acoustics we are concerned with a limited number of spot frequencies and much of the work has been concentrated at, or close to, one of these ie 38 kHz. Although it is convenient to talk about one frequency, an echo-sounder cannot work unless it operates within a band of frequencies and the one always quoted is nominally the centre frequency of the band. Thus the power is transmitted simultaneously at all frequencies within the bandwidth and this is discussed in greater detail later in 3.1.2.

The frequency of a sinewave is independent of the medium into which it is introduced i.e. the number of cycles to pass a fixed point in one second is constant. But another characteristic of a sinewave, the wavelength (λ), is completely dependent on the physical properties of the medium through which the wave is propagated. This is because the wave speed is governed by the density and bulk modulus of elasticity of the medium.

Wavelength is defined as the distance between adjacent peaks or troughs of a sinewave, Figure 12, i.e. the physical measurement in metres (m) relating to this distance, the faster the wave travels the greater is λ. When we choose a frequency of operation for an echo-sounder we know that the medium into which it will operate is water, so it is possible to calculate the wavelength within fairly close limits if the speed of acoustic waves in the particular volume of water is known. This is because the speed (c) of wave travel is related to frequency (f) and wavelength (λ) as shown in eqn. 11 i.e. $\lambda = c/f$.

The importance of wavelength becomes apparent in the next section where we discuss some of the effects of acoustic wave interaction with fish.

Figure 12.



2.8 Acoustic Waves and Fish

When an acoustic wave strikes a fish a proportion of the energy is reflected and this is called the echo. The factors on which this quantity depends are not entirely understood, but in this section we consider some of the basic theory.

When a plane wave meets a boundary of two different media e.g. the water and the fish body, it may be partially reflected. If the fish has dimensions of the same order as the acoustic wavelength, the intensity reflected in any particular direction depends on the impedance ratio of the water and fish, also the shape and orientation of the fish.

To begin, we assume that the fish remains the same shape whilst its interaction with the acoustic wave occurs. Thus we can look at the directional pattern when the orientation of the fish changes with time. If an abitrary reference axis passes through a fish whose orientation is being varied and the amplitude of the echo is measured as a function of the direction of this axis, the result can be plotted as a polar diagram. A hypothetical plot is shown in Figure 13(a), but of course this is for one plane only, the whole diagram is three-dimensional and would look roughly like a ball with projecting lumps. The next figure 13(b) shows the same result as before but plotted on a linear angular scale.

Figure 13.

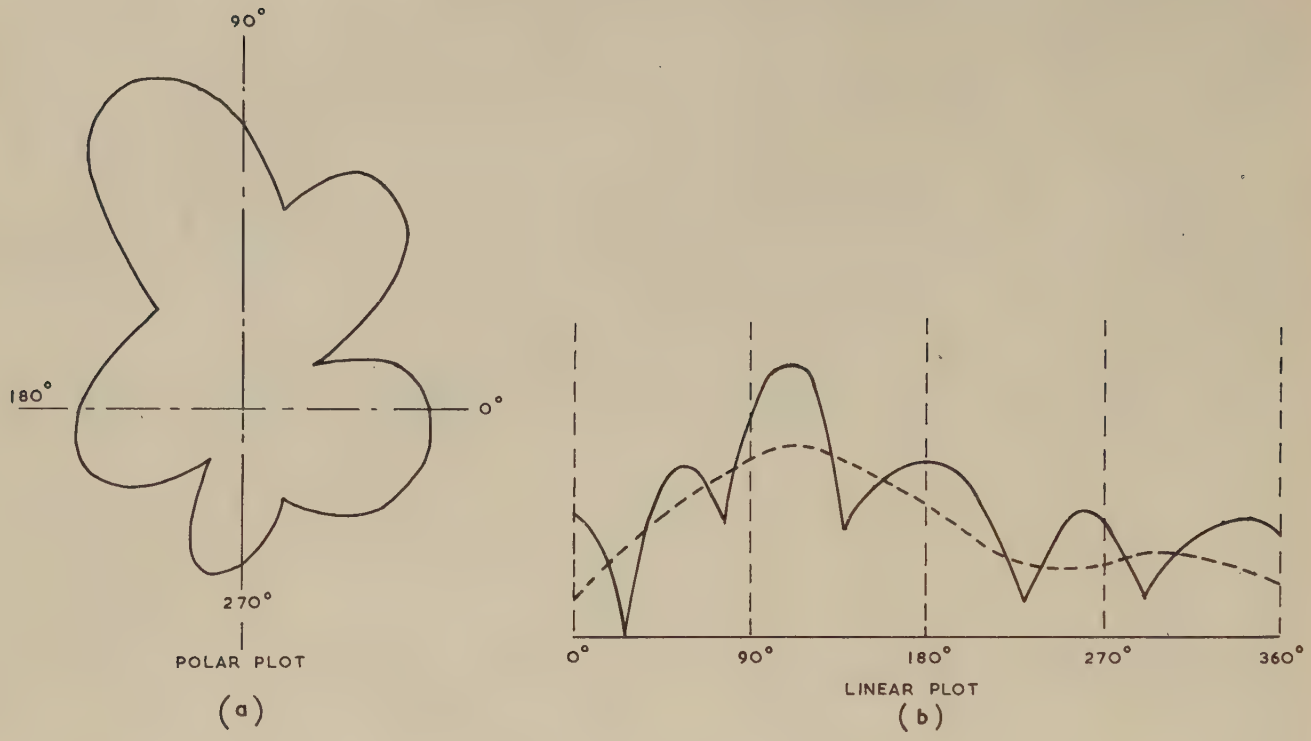
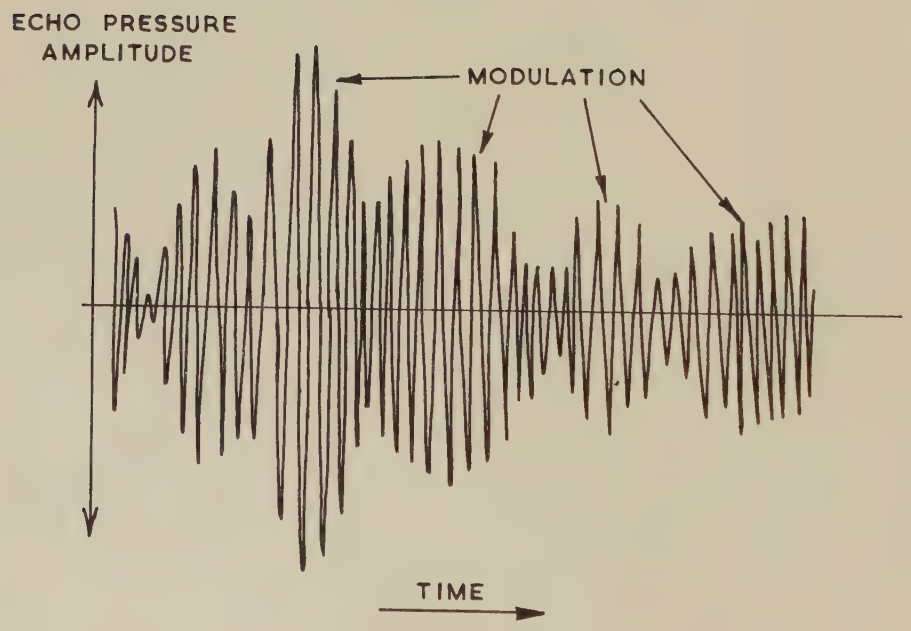
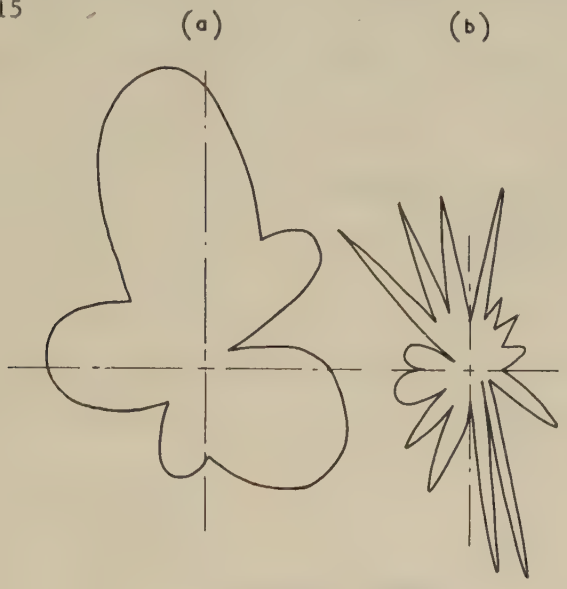


Figure 14



If the fish were steadily rotated in the plane for which Figure 13 was drawn, the echo amplitude would fluctuate and the effect would be to modulate the echo wave. To modulate means to 'impress information upon' and this is seen in Figure 14 where the fluctuations of the high frequency acoustic wave amplitude are due to the information' about the number and relative size of the lumps, or lobes of the directional pattern.

Figure 15



PATTERNS OF DIFFERENT ANGULAR FREQUENCY

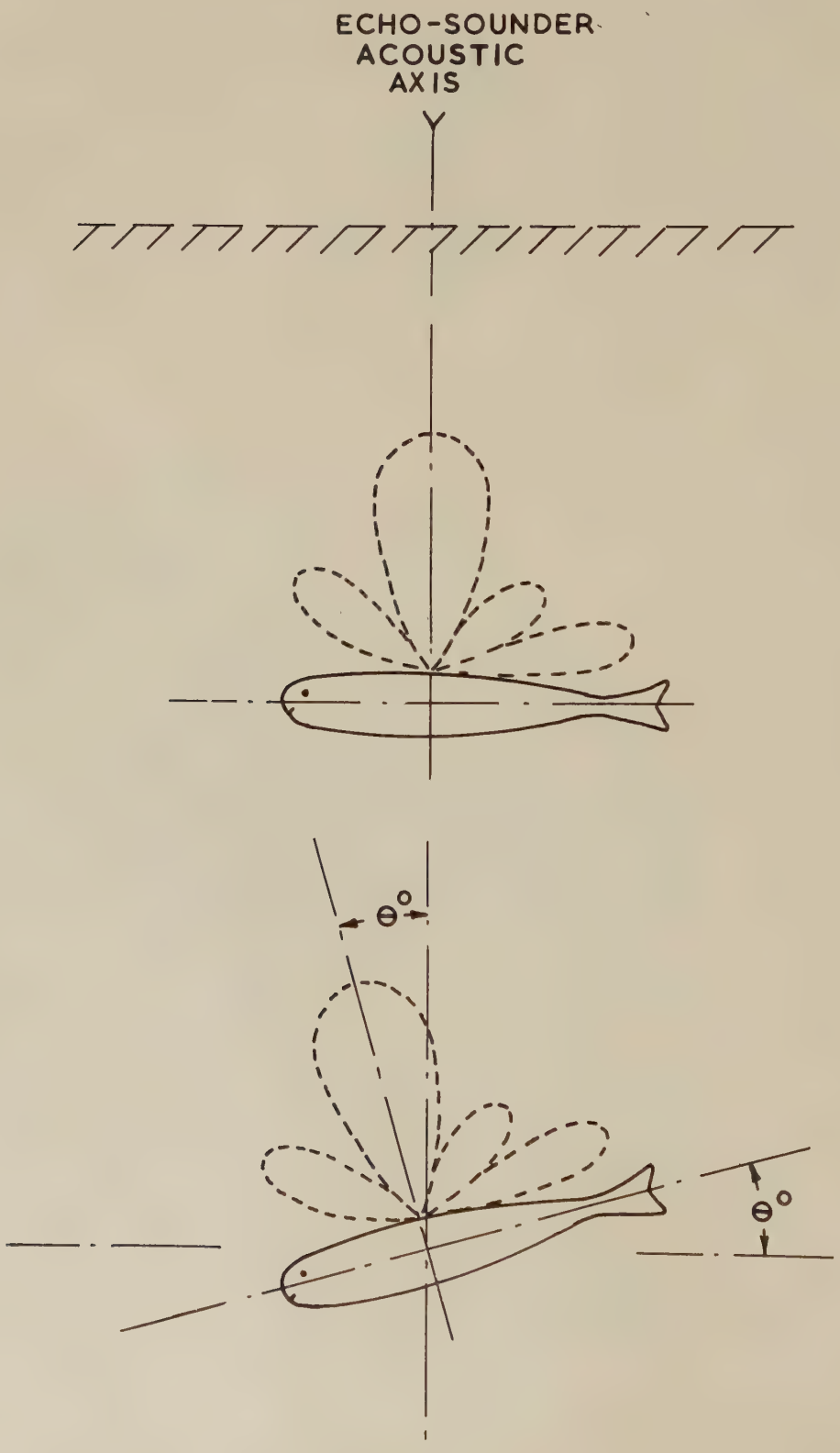
A fundamental property of such patterns is the closeness of the lobes and hence the rate at which successive maxima and minima of the echo occur as the fish rotates, ie the angular frequency of the lobes. Patterns with different angular frequencies are shown in Figure 15a and b, and it is clear that (b) has a much higher angular frequency than (a) which will lead to more rapid fluctuations of the echo. A fish could possess both of these patterns because it has a large dimension in one direction and a much smaller dimension at right angles to this, but in practice we are usually concerned only with small variations about the dorsal aspect.

The presence of a fish in the 'acoustic field' (the surrounding acoustic waves) has the effect of changing the field around the surface of the fish by adding what is called the perturbation field (perturbation means greatly disturbed). It is as if the perturbation field arises from virtual sources of acoustic energy inside the body of the fish. In other words, the fish appears to generate an outward-radiating wave system by extracting a flow of energy from the passing incident waves and re-radiating it in all directions. Around the surface of the fish the perturbation field has a 'waviness' which matches the waves of the incident field so of course there are a finite number of wavelengths occurring in relation to the length of a fish. The number of lobes in the directional pattern is dependent on the size of the fish in wavelengths, not its absolute size e.g. at 38 kHz a 40 cm fish is 10 wavelengths but at 120 kHz it is 32 λ. The size of the lobes, on a relative amplitude scale, is determined by the fish size.

Although there is a maximum possible amplitude of echo from any particular fish, the actual size received depends on the angle of the lobe, or lobes of the directional pattern 'pointing' in the direction of the echo-sounder acoustic axis, see Figure 16.

Discussion so far has assumed that the fish remains the same shape, but this is not true, the shape changes with time as the fish swims. The effect is that the virtual sources within its volume change position slightly which causes another kind of modulation to the echo amplitude. Thus it is clear that trying to predict, or model the response from fish is difficult so we have to make measurements, either of individuals, or known quantities and this is discussed later in section 4.5 and 4.6. Section 2.8 is based on notes written by the late Dr V. G. Welsby. The next chapter deals with the instruments needed for fisheries acoustics.

Figure 16



3. PRINCIPLES OF INSTRUMENTS FOR FISHERIES ACOUSTICS

Echo-sounders transmit a pulse of acoustic energy down towards the seabed and measure the total time taken for it to travel through the water, i.e. the outwards and return journey. If the measured time is one second and it is known that the speed of acoustic waves is 1500 m/s, the depth is obviously (1500 x 1)/2 metres = 750 m.

By using a recorder with slowly moving paper to display the time of transmission and then the echoes as they return, a past history of the depth and of the sea bed topography is built up. If the system is sufficiently sensitive it will also display the echoes from fish, but this gives merely an indication of their relative abundance. Instruments capable of making quantitative acoustic measurements are needed, together with methods of turning these into figures of the absolute fish abundance. To do this, echo-sounders with precise characteristics have evolved. Their signals are coupled to a specially developed instrument, the echo-integrator, which selects and processes them in various ways. In this section we first consider the echo-sounder.

3.1 The Echo-Sounder

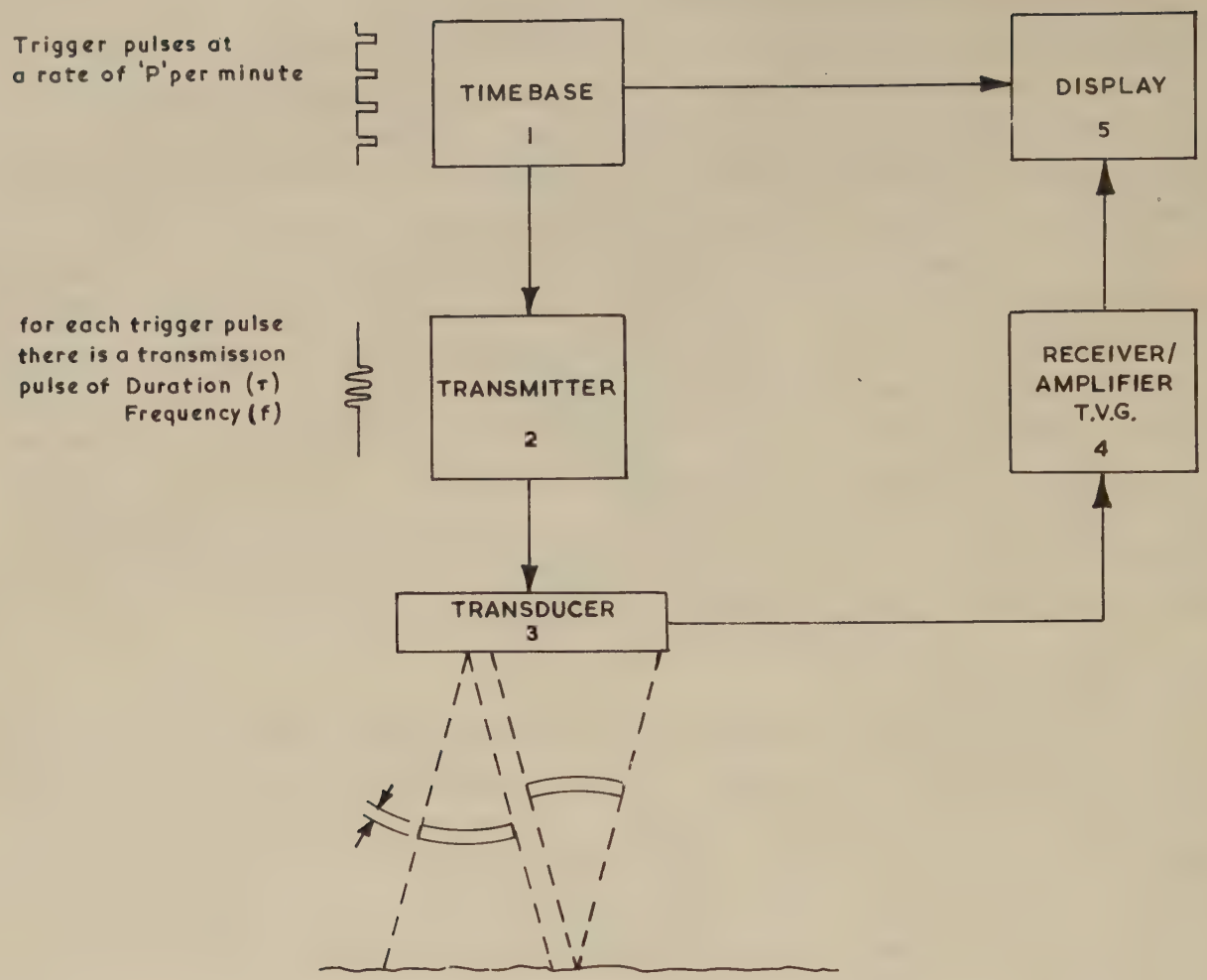
There are many units, each with distinct functions, which combine to form a complete system for the measurement of acoustic signals related to aquatic biomass. The echo-sounder comprises a transmitter, transducer, receiver amplifier and timebase/display. Figure 17 is a block diagram showing the interconnection of these units. Blocks 1,2,4 and 5 are usually contained within the same cabinet and it often requires only the connection of the transducer (block 3) to enable soundings of depth to be taken. The operation is as follows.

The timebase (block 1) initiates an electrical pulse to switch on (modulate) the transmitter, which in turn produces a pulse of centre frequency (f) and duration (τ), to energise the transducer (block 2). Electrical energy is converted by the transducer into acoustic energy in a pulse of length $c\tau$ which is beamed into the water, insonifying objects in its path. Echoes from these objects return, to be converted back to electrical pulse signals by the reverse process in the transducer. These signals are normally very small so they are amplified, but in a selective way, relative to the time they occurred after transmission (time-varied-gain, TVG). This compensates for the power losses when travelling out and then back to the transducer. After the TVG process, signals are demodulated (detected) i.e. the information they contain, amplitude and duration is extracted. In this form signals can mark a paper, or be processed by an echo-integrator. Now we consider the units in detail.

3.1.1 Time base

One function of a time base (block 1) is to provide the 'clock' which sets the accuracy of depth measurement, the other is to control the rate (P) at which transmissions are made.

Figure 17



BLOCK DIAGRAM OF A BASIC ECHO-SOUNDER

In section 2.7 we saw that, except for extreme conditions, the effects of salinity and temperature on the speed of an acoustic wave are not very significant for fisheries surveys. This means that the speed of the timebase 'clock' can be set in relation to a nominal speed of acoustic waves and 1500 m/s has been adopted for most marine purposes. This speed is exact for a temperature of 13°C and a salinity of 35°/oo (see Figure 9). At the extreme temperatures shown on this figure (but with the same salinity of 35°/oo) depth errors of about 3% would occur, i.e. at 30°C the recorded depth would be 3% shallower than the true depth and the opposite at 0°C. The timebase may consist of a 'constant' speed motor driving a pen across recording paper, or an electronic circuit controlling the spot of light moving over the face of a cathode-ray tube. In either case it is also used to initiate the 'trigger' pulse which marks the point of transmission i.e. zero on the depth scale.

The trigger pulse is so-called because it 'fires' or 'triggers off' the transmission from the echo-sounder. This is important because it must always occur at a precisely defined interval of time, chosen so that the rate of transmission (P) pulses per second, sometimes called pulse repetition frequency (PRF) is suitable for the depth of water to be surveyed. That is, a long enough interval between pulses for all the echoes resulting from one transmission to have returned, before the next transmission. This factor is controlled by the depth selector of the echo-sounder, i.e. the manufacturer arranges a suitable PRF for each depth scale.

3.1.2 Transmitter

The transmitter (block 2 of Figure 17) is triggered from the timebase at a rate of P, pulses per second. Each 'trigger' starts the pulse duration circuit (symbol τ), it runs for a selected time and during this time the actual echo-sounder frequency is coupled to the power amplifier which is in turn connected to the transducer. A specific number of cycles at the correct frequency are released by the pulse duration circuit. If the frequency is 38 kHz we know from section 2.7 that the periodic time, t (time taken to complete one cycle) is $t = f^{-1}$ i.e.

$t = 1/38000 = 26 \times 10^{-6}$ seconds or 26μs.

If 20 cycles are transmitted, the pulse duration

$\tau = 20 \times 26\ \mu s = 520\ \mu s$ or 0.52 ms.

We know that acoustic waves travel at a speed (c) of 1500 m/s so the distance covered in this time is

$$c\tau \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (12)$$

which in the present example is

$1500 \times 520 \times 10^{-6} = 0.78$ m pulse length

i.e. the actual physical length of the pulse in the water.

This is an important parameter of a fisheries echo-sounder because

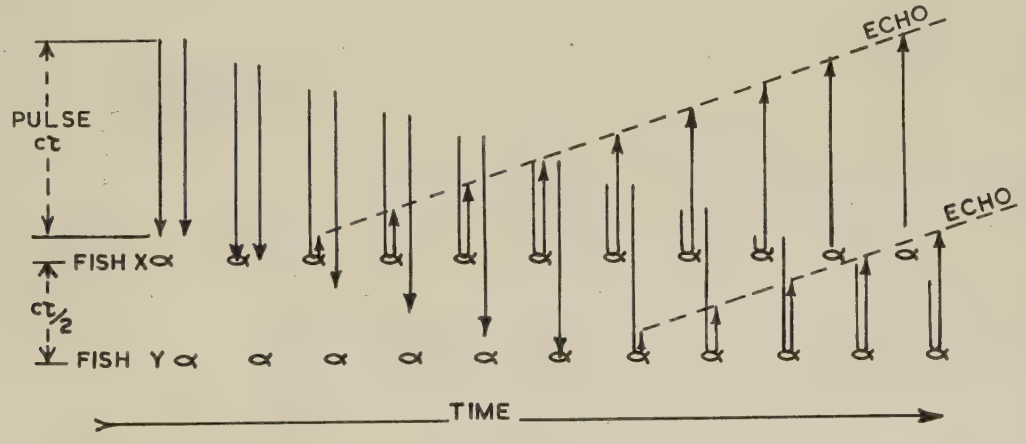
(a) it determines the vertical (depth) resolution between targets, i.e. between one fish and another, or between a fish and the sea bed. The minimum distance between any objects X and Y, sufficient for their echoes to be separated is

$$c\tau/2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (13)$$

this is shown in Figure 18 and discussed further in Section 9.4.2. The shorter is τ, the better the resolution.

(b) it affects the transmitted energy. The longer the pulse in the water the greater is the chance of detecting targets at long distances because the average power is increased.

Figure 18.



There are physical limitations to the minimum pulse duration which can be used and to the amount of power it is possible to transmit, which are not related to the transmitter.

A power amplifier within the transmitter raises the power output to some hundreds of watts, or even a few kW and this power level must remain exceptionally constant. It is measured with the transducer connected, either by taking the peak-to-peak voltage, converting it to rms, then squaring it and dividing by the transducer resistance RR (see section 3.1.3 about RR).

$$\text{Power} = V^2_{rms}/RR \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (14)$$

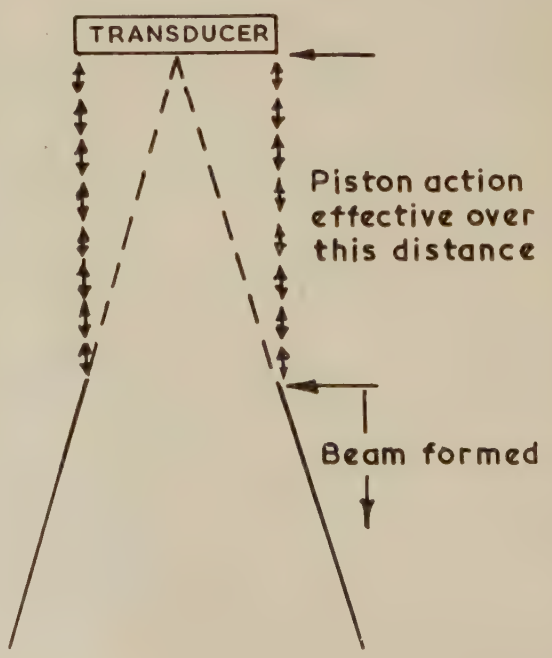
or, it may be more convenient to read peak to peak voltage directly, then

$$\text{Power} = (V^2 \text{ peak-to-peak})/8RR \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (15)$$

3.1.3 Transducers and Acoustic Beams

Although there are separate transmitter and receiver circuits within all echo-sounders it is normal to use only one transducer for both transmission and reception. A transducer can be described as an energy converter; during transmission its input is electrical and its output is acoustic; for reception the input is acoustic and the output electrical. It is similar in function to a combined loudspeaker and microphone, but the different acoustic properties of water mean that it is not possible to use the same designs. Also, a much higher efficiency of energy conversion is possible in water than in air. When used for transmission the transducer is known as a projector, and when receiving, it is called a hydrophone. Underwater transducers use an effect whereby the actual dimensions of a piece of material change under the influence of either a magnetic (magnetostrictive), or electric (electrostrictive) field. If the field follows the electrically applied oscillations the resulting change in dimensions will generate acoustic pressure variations at the same frequency. The opposite effect occurs when an acoustic echo acts on the face of a transducer, the dimensions change, producing a voltage across the terminals which varies in sympathy with the echo.

In the region close to the transducer face the axial acoustic intensity varies in a complex way between maximum and minimum levels. As the transducer expands, it exerts pressure on the water immediately in contact with it, thus causing compression. When the transducer contracts, the pressure is reduced, causing rarefaction. These effects of compression and rarefaction are projected forward, still contained within dimensions equal to those of the transducer face until a distance, as illustrated in Figure 19 is reached. The volume contained within this distance and the dimensions of the transducer face is known as the near-field.



Within the near-field (sometimes called the Fresnel diffraction zone) and far-field for that matter, the distance from any edge of the transducer face to a point on the axis is greater than the distance from the face along the axis to the same point. If we consider the variation in distance to a given point for all the vibrations leaving the transducer face it is possible to visualise the interference effects which arise and cause the maxima and minima of acoustic intensity to occur. For practical purposes the near-field ends and the far-field begins at a distance R of

$$R = 2L^2\lambda^{-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (16)$$

where L is the length of the longest side of a transducer, or its diameter

λ is the wavelength

both L and λ in metres.

The minimum distance for measurements is shown in Chapter 7, Figure 44

Acoustic intensity from a projector is greatest on the axis of the beam (Figure 20), it decreases as the angle from the axis increases, until the first zero of the response pattern is reached. Beyond the angle of this zero is the first sidelobe which itself goes to zero at a still greater angle and the pattern continues, each sidelobe having a progressively smaller response the greater its angle from the axis.

The beam angle is not usually measured to the first zero for reference purposes, it is always measured to the angle where the response is half that on the axis.

$$10 \log 1/2 = -3 \text{ dB}$$

and the reference angle is quoted as the half angle $\Theta/2$ to the half power level, i.e. from the axis to the angle where the response is -3 dB. In Figure 20 a polar diagram of an actual transducer response is shown which illustrates the relationship of the main lobe and sidelobes, when $L >> \lambda$ the full beam angle Θ can be calculated to a good approximation from

$$\Theta = 57.3\ \lambda L^{-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (17)$$

where L and λ are in m

Θ is in degrees

57.3 is the number of degrees in a radian

λ is the wavelength

L is the diameter of a circular face, or the length of a rectangular face.

By re-arranging this we can find the length of the active face of the transducer whose pattern appears in Figure 20.

$$L = 57.3\ \lambda\Theta^{-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (18)$$

Of course, if the transducer is rectangular it will have a different beam angle in the front to back direction to that in the side-to-side direction. However, assuming the above transducer is circular (diameter L) and is resonant at 38 kHz,

$$\lambda = cf^{-1} = 1500 \div 38 \times 10^3 = 3.95 \times 10^{-2} \text{m}$$

$$L = 57.3 \times 3.95 \times 10^{-2} \div 12.5 = 0.18 \text{ m}$$

A general rule with transducers is that, the narrower the beam the larger is the transducer.

Figure 20.

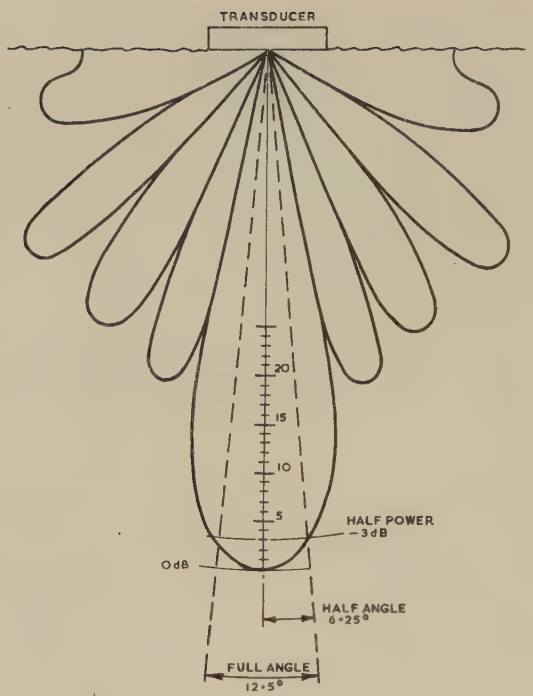
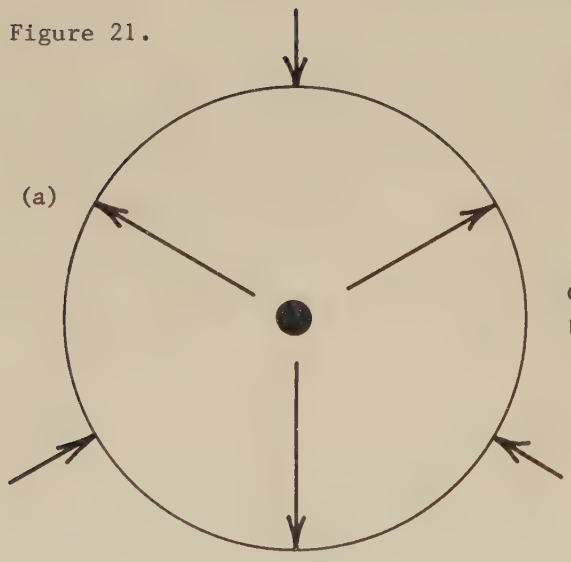


Figure 21.

(a)



OMNIDIRECTIONAL
DI = 10 log 1/1 = 0dB

(b)

HEMISPHERICAL
DI = 10 log 2/1 = 3dB

(c)

CIRCULAR FACE
$DI \approx 10 \log (2\pi a \lambda^{-1})^2$

RECTANGULAR FACE
$DI \approx 10 \log 4\pi A \lambda^{-2}$

A property of transducers, related to the beam angle, is the directivity index DI. For the present purpose it can be defined as the ratio of acoustic intensity transmitted or received by a transducer of full beam angle Θ, to that of an omni-directional transducer. In other words it is a measure of the extent to which transducers can concentrate transmitted or received acoustic power. Figure 21 illustrates this.

For a circular transducer the approximate expression for DI is

$$DI = 10 \log(2\pi a \lambda^{-1})^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots (19)$$

where a = radius in m

λ = wavelength in m

Applying this to the transducer above

$$DI = 10 \log((6.28 \times 0.18/2) \div 3.95 \times 10^{-2})^2 = 23 \text{ dB}$$

When the transducer is square or rectangular and the length of the shortest side, $L \gg \lambda$, then

$$DI = 10 \log 4\pi A \lambda^{-2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (20)$$

where A = area of transducer face

if the beam angle is known, but the area is not

$$DI = 10 \log 4\pi/(\Theta_1/57.3)(\Theta_2/57.3) \quad \ldots\ldots\ldots\ldots\ldots\ldots (21)$$

where Θ_1 (degrees) is the full beam angle in one direction

Θ_2 " " " " " " " the other direction.

An important property of transducers is their frequency response. Transducers used for fisheries survey purposes are resonant at a particular frequency, often called the echo-sounder frequency e.g. 38 kHz. But if they only responded to this one frequency it would be necessary to use an infinitely long transmission which would make echo-sounding impossible. At the other extreme, if we tried to use an infinitely short pulse, the transducer would need to respond to an infinite number of frequencies. This is because a square pulse is made up from an infinite number of different frequency sine waves. Fortunately, a reasonable shape of pulse can be achieved with a relatively small, finite number of frequencies so a compromise can be made.

The design and construction of a transducer determines its frequency response, or bandwidth (BW) as it is known. Bandwidth is defined as the number of Hz between the frequency, at each side of the resonant frequency, where the tranducer response is -3 dB of the maximum. It is not possible to change the transducer bandwidth which means that

(a) there is a minimum pulse duration

(b) there is a maximum receiver amplifier bandwidth. (See next section.)

The shape of the bandwidth curve is controlled by a factor called Q.

$$Q = \text{Resonant frequency}/f_2 - f_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (22)$$

f_2 is the highest frequency where the response = -3 dB

f_1 " " lowest " " " " " = -3 dB.

Typically Q might be 10 to 15 for a 38 kHz transducer.

In order to pass a pulse without reducing its amplitude and excessively distorting its shape the minimum bandwidth must be

$$BW = 2\tau^{-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (23)$$

Assuming Q = 10 and f = 38 kHz (the resonant frequency)

BW = 3.8 kHz

the value of pulse duration to match this is

$\tau = 2/(BW)^{-1} = 2/3.8 \times 10^3 = 526 \times 10^{-6}$ ie 526 μs or 0.526 ms

Note that, whilst it is necessary to have a wide bandwidth to preserve pulse shape, the greater the bandwidth the more noise is let into the receiving system. This point is discussed in chapter 4.

Two other properties of transducers are important to the full understanding of their use and application to fisheries surveys; the electrical impedance and the efficiency of energy conversion. In section 2.1 the resistance R of an electrical circuit was the filament of a lamp (the energy converter). Power in the circuit was related to the square of the voltage or current in proportion to the resistance. The function of a transducer is extremely complex but in principle the method of calculating the power input is similar to that applying to the lamp. A transducer does not present a simple resistance at its terminals, instead it has an impedance. This term is used when there is a combination of resistance and reactance (resistance to AC) in a circuit. The effect of the reactance is frequency dependent but it does not dissipate power, it impedes the flow of current according to the frequency. Its effect is cancelled by use of an equal reactance with an opposite sign. What we need is the value of the effective resistance, usually called the radiation resistance (RR) of the transducer. It is not a simple operation to measure RR but manufacturers normally provide this figure to enable power calculations to be made.

Transducer efficiency (η) is defined as the percentage of power output to power input whether this is electrical to acoustic (transmission), or the reverse (reception). Typically the efficiency of magnetostrictive transducers is 20 to 40% and electrostrictive types, 50 to 70%.

The sensitivity of a transducer (SRT) as a receiver of acoustic waves is expressed in terms of the number of dB with reference to one volt for each micropascal of pressure, i.e. dB/1 Volt/1μPa. It is normal for SRT to have a value somewhere in the range of -170 to -240 dB/1 Volt/1μPa (-170 is the most sensitive of these). An approximate figure is given by

$$SRT = 20 \log (2.6 \times 10^{-19} \eta A RR)^{\frac{1}{2}} \text{ dB/1Volt/1}\mu\text{Pa} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (24)$$

where η is % (e.g. 50% = 0.5)

A is the transducer face area in m^2

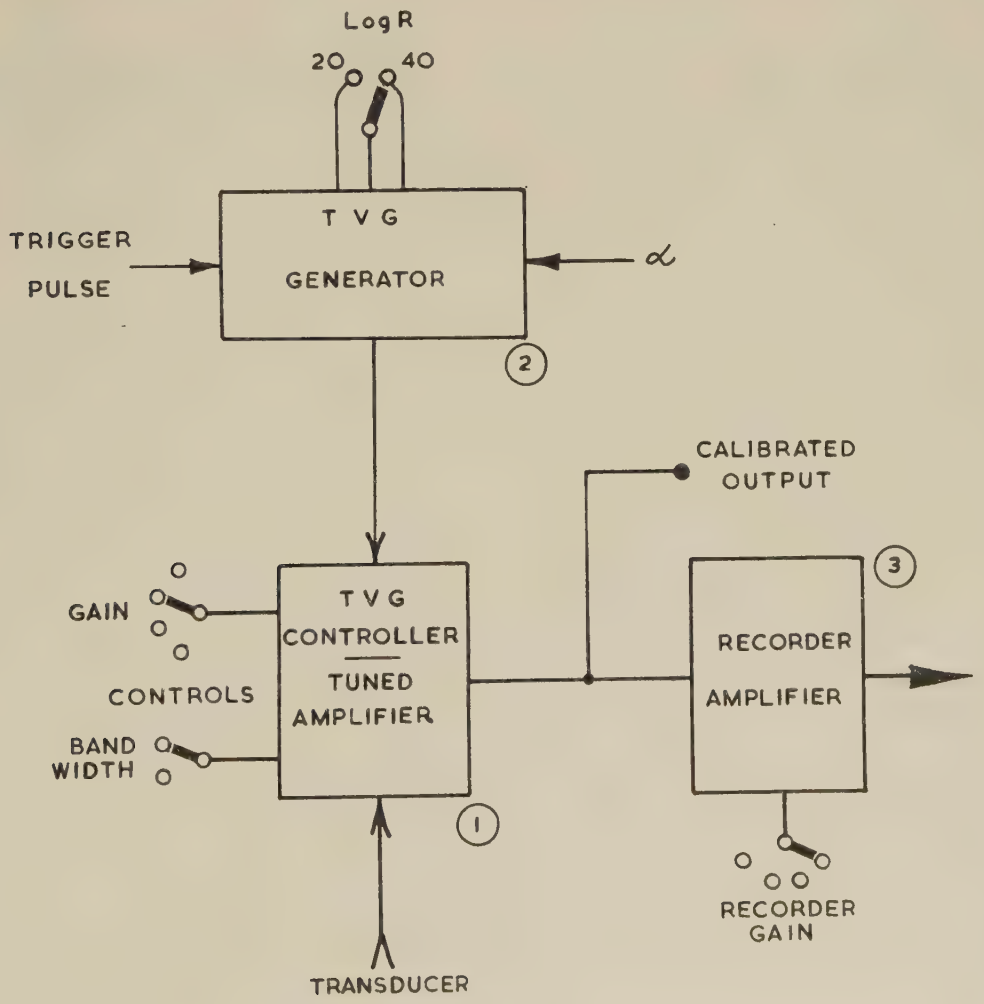
RR is the radiation resistance in ohms.

This is an appropriate point to consider the receiving system beyond the transducer.

3.1.4 Receiver Amplifier

This is block 4 of Figure 17, usually the most complex electronic unit in the echo-sounder. A diagram illustrating the receiver amplifier principal functions appears as Figure 22. The purpose of the complete unit is to amplify the signals VRT received from the transducer in a precisely controlled manner and to present them to the following instruments (the echo-integrator or echo-counter) at a suitable level of amplitude for further processing.

Starting at the input of block 1 of Figure 22, the transducer output is electrically matched to the input of the receiver, i.e. in terms of impedance and frequency bandwidth. Sometimes the receiver bandwidth is controlled by means of a switch to closely match the transmitted pulse duration τ, $BW \approx 2\tau^{-1}$. Although quoted at the -3 dB response points on Figure 22



either side of resonance in the same way as a transducer, the receiver bandwidth is often controlled until the response is at least 40 dB down on the maximum. Usually a 'bandpass' form of response is provided because it only allows those frequencies which lie within the wanted band to pass from the input, thus minimising the effects of high level wideband interference.

Overall amplification, or gain factor G is defined as

$$G = 20 \log VR/VRT \text{ dB} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (25)$$

where VR is the output voltage

VRT is the minimum detectable voltage from the transducer.

The overall receiver response is defined as the voltage VR (dB/1Volt) relative to an acoustic intensity of 1μPa at the transducer face. Gain must be precisely controlled in relation to depth and blocks 1 and 2 of Figure 22 automatically vary the tuned amplifier gain relative to the time after transmission. This is known as time varied gain TVG and the circuits comprising it are the TVG generator and controller, see sections 4.2; 7.2.2. At the beginning of each sounding period the transmitter trigger pulse also starts the TVG generator control circuit (block 2) after a fixed delay, often at 3 m depth but it can be less.

Modern TVG circuits operate digitally; for each small time increment there is a corresponding change of gain in the amplifier, the rate of change depending on which TVG law is in use, see section 4.2 for details. With a correctly functioning TVG the calibrated output voltage VR from the receiver amplifier is independent of the depth to the target, preferably to an accuracy of ±0.5 dB or better at any depth over which the TVG is designed to operate. This is of course provided that the TS of a target does not itself vary with depth.

In addition to the trigger pulse which initiates timing at the beginning of each sounding period, there is another input to the TVG. This is the absorption coefficient α for which the TVG circuits must compensate. A value for α is determined at the start of a survey and switched, or keyed, into the TVG circuit where it remains the same until conditions change sufficiently that it must be updated, see section 2.6.1.

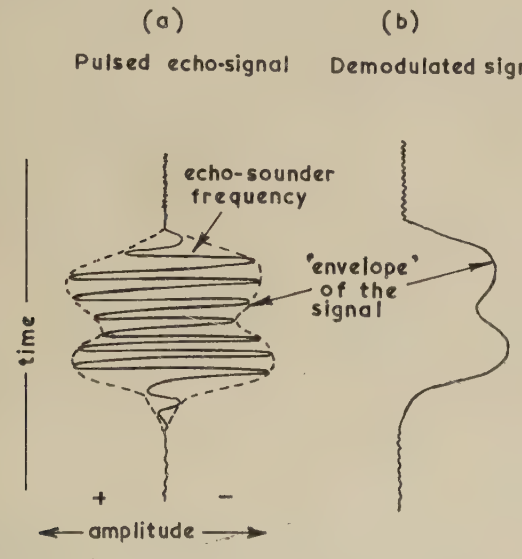
All amplifiers produce some noise, i.e. with no input signal from the transducer, or with merely a matched resistor replacing it, there will be some noise at the output; the receiver self noise. This electrical noise must always be below the lowest level of acoustic noise likely to occur from a very low sea state when the ship is stationary, or, when working at higher frequencies, the thermal noise level, see section 4.7. Receiver self-noise can be quoted as less than -n dB/1Volt referred to the input terminals but with a TVG amplifier is not constant. Modern receiver amplifiers generally have input sensitivities of 1μV or less, i.e. -120 dB/1Volt or less.

The maximum depth at which a given size of target can be detected is the point where it is just distinguished above the noise level, but for acoustic survey purposes the SNR must be greater than 10 dB. At the other extreme there is a maximum size or density of

target with which the receiver can cope at short range due to the saturation level of the circuits. Receiver saturation is defined as the condition when the output voltage no longer follows the input voltage linearly, i.e. the gain factor is not constant. It is vital that the receiver voltage response (gain) is linear between the extremes of signal level (> 120 dB) likely to be encountered under practical survey conditions. The difference between the minimum useable signal at the receiver input and the maximum input signal which does not cause saturation is the dynamic range. A typical output signal dynamic range might be between 50-80 dB. For measurement purposes the output voltage VR is always taken from the calibrated output but there is usually another amplifier which processes the signals for display purposes, either a paper recorder or a rectified 'A' scan cathode ray tube display.

3.1.5 Displaying and Recording Signals

Figure 23



Once amplified, the echo signals are still in the form of a pulse comprising a certain number of cycles at the echo-sounder frequency, Figure 23(a). For display purposes only this pulse at the echo-sounder frequency is further amplified then demodulated, otherwise known as 'detected', or 'rectified', Figure 23(b). This process removes all traces of the echo-sounder frequency, and, either the positive half of the negative half of the pulse. The result is a uni-directional DC waveform which can be used to mark a paper record, or to deflect the beam of a cathode-ray tube (rectified 'A' scan). An unrectified 'A' scan CRT would take its signals from the calibrated output.

Signals cannot be displayed intelligibly without a timebase. The function of a time base was described earlier although it is usually an integral part of a display. There are multi-stylus 'comb' recorders which use an electronic time-base, but some recorders of scientific echo-sounders still have a mechanical timebase. In these systems a motor and gearbox drive a marking stylus across electrosensitive wet or dry paper which is slowly drawn over a metal plate, at 90° to the path of the stylus.

As the stylus rotates, or moves past the zero mark on the recorder scale the transmitter 'trigger' contacts operate, causing an acoustic pulse from the transducer. Whilst the stylus continues to move across the paper, echo signals start to return and mark the paper at the instant they arrive. When the stylus reaches the zero mark again, the paper has been drawn along so that successive soundings are just separated from one another giving the familiar record. A recorder timebase normally generates time marks

and for acoustic survey purposes it is important to have an input from the ship's log to mark the paper at the end of each nautical mile or some other unit of time or distance.

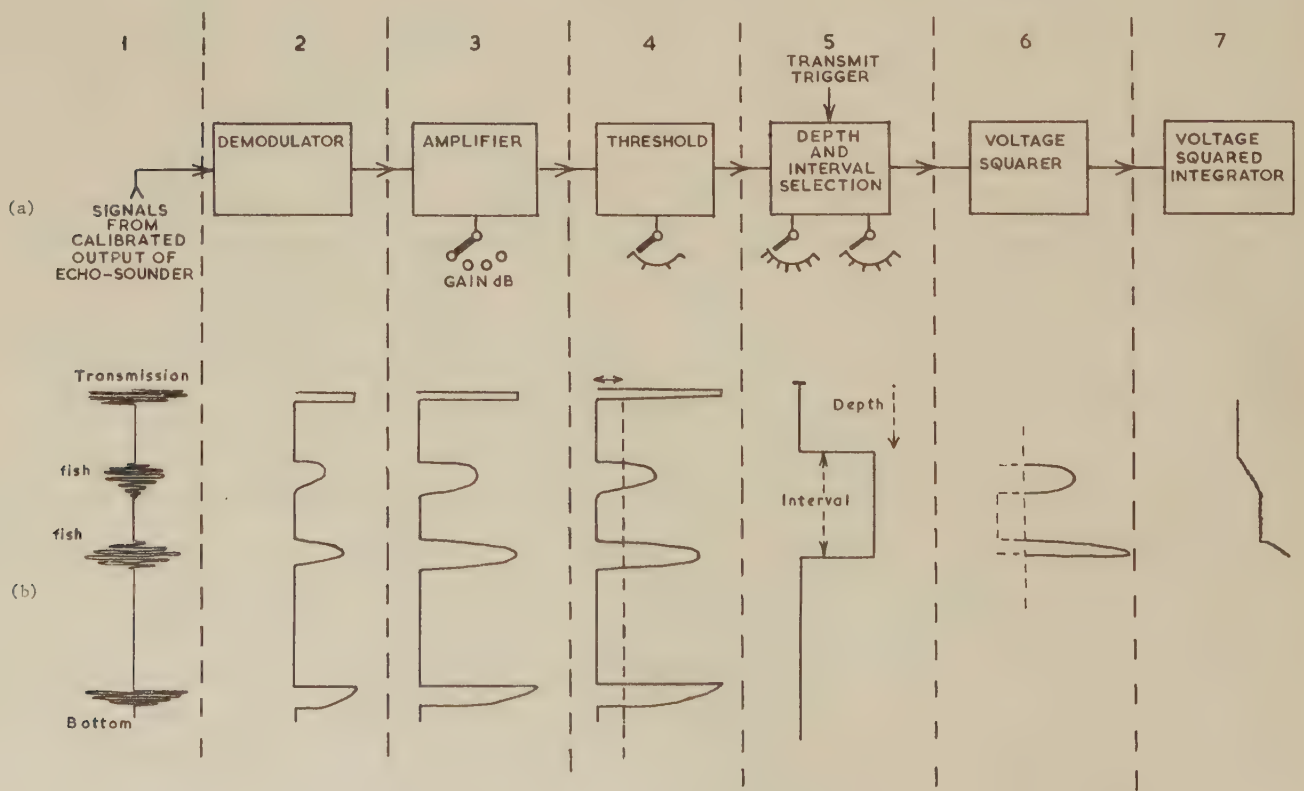
3.1.6 Recording Paper

Moist paper is sensitive to weak signals and has a good dynamic range relative to dry paper (the ability to show a range of different colouring according to the signal strength). It is still widely used despite a number of disadvantages. These are

1. Moisture content must be carefully controlled during manufacture
2. Careful packaging and storage before use
3. Must be 'sealed' in the recorder to retain moisture
4. Shrinks when it dries
5. Fades quickly and discolours if exposed to light.

Stylus pens for moist paper have 'thick' polished tips and are applied to the paper at a constant pressure. Compensation is made for the change of marking density with change of speed of rotation. Dry paper is prepared with electrically conductive surfaces and a filling of fine carbon powder between them. A fine wire stylus conducts a high voltage to break down the front surface paper and make a dense black mark. Although this marking process is difficult to control and consumes the stylus, less storage problems occur before and after use. Dynamic range is about 10 dB whereas nearer 20 dB is claimed for the moist paper. Multistylus recorders can use either wet or dry paper.

Figure 24. (a) Block schematic diagram of an analog echo-integrator
(b) the wave forms associated with each block



3.2 The Analog Echo-integrator

Echo-integrators were first used in the late 1960's when only analog techniques were practicable. Despite the introduction of a number of digital integrators many analog units are still in use. Because of this the essential functions of signal processing and echo-integration are first described by reference to the Simrad QM system. A brief description of the main features of the digital units is then given in section 3.3.

An echo-integrator receives all signals from the calibrated output of the echo-sounder, see diagram 1 of Figure 24. These signals require further processing and the facility for the operator to select sections, or intervals of the water column at depths which can be adjusted to make the echo-integrator into a practical tool. Because of this there are many circuit functions, of which only one is strictly an integrator, but it is convenient to place them together and call the resulting system of units an echo-integrator. The term integrator is used in its mathematical sense of measuring the area under a curve of voltage versus time. Time is usually proportional to the distance moved by the survey vessel and the voltage output is proportional to fish density. A block diagram showing the main functions of an echo-integrator appears in Figure 24(a) and the associated waveforms in 24(b).

3.2.1 Demodulator

When the TVG controlled signals from the calibrated output of the echo-sounder reach the echo-integrator, they still consist of sinewaves at the echo-sounder frequency. It has been shown that a sinewave has equal positive and negative values and the information it carries (the modulation) is in the form of equal positive and negative changes of amplitude. The integral of a sinewave is zero, so before integration the information must be changed to a different form. This process is known as demodulation, sometimes called detection, or rectification, Figure 23(a)(b) and block 2 of Figure 24.

This completely removes either the positive or the negative portions of the signal so that only variations between zero and one polarity occur, but these are still at high frequency. A further process filters out the high frequency half-cycles and we are left with the average voltage (i.e. an 'outline' of the signals) of varying amplitude according to the signal strength. In section 3 of Figure 24 there is an illustration of the waveform in section 1 when it has been demodulated. After this process there may be a need to amplify the signals.

3.2.2 Amplifier

Survey conditions in regard to density of fish and depth at which they occur can vary widely so it is sometimes useful to have an amplifier (block 3) to increase the amplitude of the signals by a precisely known amount. If a thin layer of widely spaced targets is to be integrated, the signals may be very small so that the subsequent processing cannot be carried out efficiently. Any change of signal amplitude is important so a switched type of control is necessary allowing say, 0-10-20-30 dB of amplification to be used. These steps of gain correspond to amplitude changes of 1, 3.16, 10 and 31.6 times respectively.

3.2.3 Threshold

This function, block 4 of Figure 24, is linked to the gain control of the amplifier to ensure similar operation at each setting of the latter. The effect of the threshold control is to vary the zero reference of the DC waveform by a small amount so as to suppress noise, which although at a low level, may exist throughout the full depth interval, thus giving rise to a significant integrated output. Of course the threshold setting must be taken into account when the final results are being calculated. However, in order to make the processing after the threshold as accurate as possible, the amount subtracted from each signal above the threshold level is added again but exact compensation cannot be achieved. The threshold control should never be used unless it is absolutely essential. When used with analogue integrators it seriously biases the obtained results in a manner which cannot be reproduced. The effect of any threshold is difficult to calculate so use of a threshold is inadvisable for quantitative measurements.

3.2.4 Depth and Interval Selection

Although the echo-integrator accepts signals from the whole water column it is necessary to have a means of excluding the transmission and the bottom echo from being integrated and this is the function of block 5, Figure 24. It is desirable to be able to select specific depth layers within the water column and to vary the extent of the layer and the depth at which it starts.

In the early equipments thumbwheel switches controlled the settings, usually in increments of 1 m. Thus a depth interval 2 m wide could be placed at a depth of 100 m for integration. The action of the depth and interval selector is initiated by the same trigger pulse which operates the transmitter and starts the TVG. It causes a circuit to operate for a duration of time proportional to the depth at which integration is required to start. When this time is reached, the first circuit causes another to operate for a time proportional to the depth interval required, this is sometimes known as an electronic signal gate. Even though the depth interval has been selected the signals are still not ready for integrating.

3.2.5 Voltage Squarer

Seen as block 6 of Figure 24 this performs one of the most critical functions in an echo integrator. It is necessary because the signal voltages V are still proportional to acoustic pressure p. Density of fish is proportional to acoustic intensity which is proportional to p^2.

Using the relationships and the analogies discussed in Chapter 2, i.e.

V is analogous to p and $V^2 \propto W$

W " " " I so $p^2 \propto I$

we can say that by squaring the voltages they become proportional to intensity. The effective gain steps of 3.2.2 are then 1, 10, 100, 1000 times, corresponding to 0, 10, 20, 30 dB respectively.

3.2.6 Voltage Squared Integrator

When the echo signal voltages have been squared, they go to block 7 of Figure 24. It is here that the energy, represented by the area under the squared voltage curve, is put into its final form of a DC voltage whose amplitude at any given time is proportional to the acoustic intensity of the signal. In Figure 24 there are two signals selected by the INTERVAL gate, the deeper of the two is partly lost because it is not completely inside the gate. The DC waveform in block 7 shows how the integrator voltage increases as the first echo rises to its maximum then falls again. When this echo finishes, the DC is maintained at the level it has reached until the next signal occurs. As shown in the waveform of block 7 the level then rises again when the second signal occurs, in this instance the rate of increase is greater than that due to the previous signal. This is because of the larger amplitude.

At this point integration is complete for the one sounding period illustrated. Although echo-integrators usually have a facility for display of single sounding integrals it is of limited value and the normal arrangement is to allow the integrals to accumulate over a given time period, or a nautical mile, after which the integrator is reset and the DC voltage starts again from zero.

3.2.7 Display of Integrated Signals

The simplest form of display possible is a DC voltmeter of either the analogue or digital type (see Chapter 7 for details) but this is not very convenient, eg when reset occurs the reading is lost. Usually a recording voltmeter is provided which displays and records the integrator output on heat-sensitive paper. In this way the variations in echo intensity can be related to positions along the ships track.

3.3 Digital Echo-Integrators

The most recent instruments developed for fish stock assessment purposes are based on digital techniques. These have similar functions to the analog system described in section 3.2 but digital instruments have greater versatility and are inherently more accurate.

Computer technology which forms the basis of digital systems is becoming commonplace in everyday life, but because of its relatively recent application to fisheries acoustics, it may pose problems to those installing, operating and maintaining such equipment until they become fully familiarised with it. Digital techniques and computer technology give high speed, accurate operation, avoiding the drift and stability problems inherent to sensitive analog systems. A digital circuit has two states only, OFF or ON, corresponding to 1 or 0 respectively. These are known as binary digits (or bits).

Signals from the echo-sounder are analog, they are changed by means of an analog-to-digital converter, (ADC) into a 'word' comprising a numbers of bits, e.g. the Simrad and Biosonics digital integrators use 12 bit words. A description of the functions carried out in an echo-integrator was made easy using the Simrad QM as an example because the waveforms throughout the system illustrate what is happening.

In a digital unit after the ADC there is nothing of this sort to visualise, there are merely the digital words being acted upon according to the inbuilt programs or operator inserted instructions.

Many of the operational features of analog integrators are found in digital systems, but they also have additional ones. The difference immediately obvious between the systems is the manner in which they are controlled. Instead of a large number of front panel controls with which to set the various equipment functions, the operator of the digital unit is provided with a computer style keyboard to type in the instructions. Inside is a computer plus a microcomputer, or microprocessor, memories for the program, the interface, a separate data memory and a data-logger sets out results on a typed record sheet.

3.3.1 Simrad QD Integrator

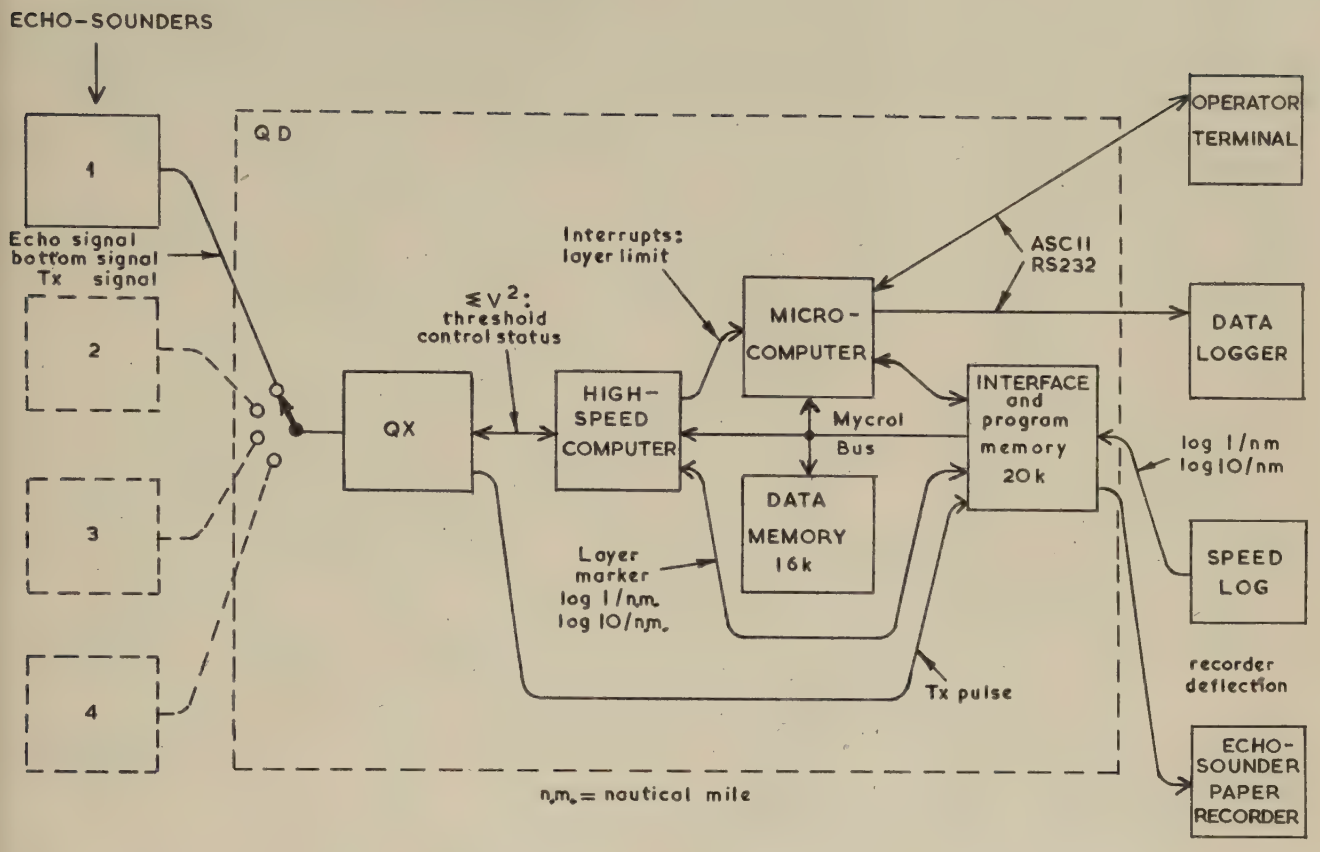
The QD equipment comprises two small rack-mounting units and a keyboard. Part of the system is called the QX Integrator Pre-processor which although specifically designed for use in conjunction with the QD in one version, can form the interface between the scientific echo-sounders and any general purpose computer in other versions.

The QX accepts inputs by push-button selection, or by software instruction, from one of four echo-sounders in the frequency range of 10-200 kHz. If the QX510/QD or QX525/NORD 10 are used, the echo-sounder can be selected by the data terminal. These combinations accept signals with a dynamic range not exceeding 70 dB, -50 to +20 dB relative to 1 Volt, ie 3 mV to 10 V. From the echo-sounder comes the bottom pulse, a transmitter trigger pulse, a digital 'hold' for the echo signal level, and an inhibit signal for echoes below the threshold level. If the input signal level exceeds +17 dB/1V, ie 7 volts, a light-emitting diode (LED) flashes on the front panel and a warning is sent to the QD. The echo-sounder signals are converted from analog to digital form before being squared, but the threshold can be applied to either the analog or the digital part of the circuit, or both. A high-performance demodulator, a 12 bit ADC, a fast-operating signal squaring unit and an accumulator for signals prior to integration are contained in the QX.

Figure 25, shows the connection to external items of equipment needed for a complete system. The labels of blocks representing major operational functions are self-explanatory, but it is not possible to judge the practical versatility, or flexibility of the system from this figure. A description of the functions starts with the way that signals are 'sorted by depth' in the QD.

1. Depth intervals or 'layers' as they are described (to avoid confusion with other types of interval in this system) can be programmed to operate down to 1000 m. Eight such layers are available in transmission-locked mode, they have a depth accuracy of 0.1 m and are sampled at each 2.5 cm of depth, ie every 33 μs in time. To set up the depth-sampling layers, the operator enters instructions through the keyboard, for the depth of start and finish of each layer and lines at the required positions appear on the echo-sounder record. The pattern of depth layers cannot be changed whilst the system is integrating, for modification the 'initial' setting up procedure must again be used.

Figure 25



Each layer may have a different threshold ascribed to it if necessary. Any two depth layers can be selected to display their integrated output in mm deflection on the echo-sounder paper record.

2. In addition to the eight depth layers referred to above, there are two bottom-locked layers which require a bottom signal of good quality, ie having a clean, fast-rising leading edge and must exceed a given amplitude. If no suitable bottom signal is received, or if strong fish echoes are likely to be mistaken for the bottom the system prevents integration. The method ensuring that the bottom contour is followed properly whilst acoustic conditions permit, depends on the generation of a so-called 'window'. Its operation may be visualised by considering a square pulse which starts just before the bottom signal and ends just after it. When the water depth is greater than 10 m, the window circuit seeks a bottom signal between +25% or -12.5% of the depth recorded by the previous bottom signal. If there are three consecutive transmissions without a bottom signal appearing in the window, it then opens from 1 to 1000 m to search for this signal, and, once found, holds it in the window again.

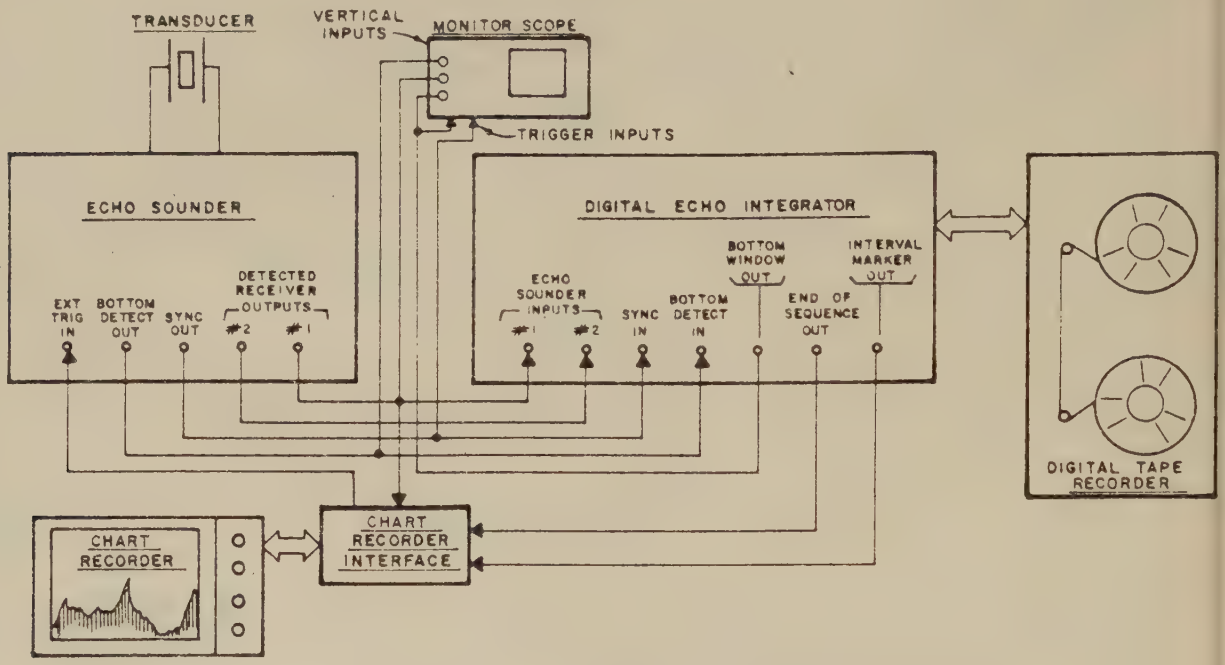
When positively identified, the bottom signal can safely be used as the time-reference to bottom-lock a layer to within 0.1 m of the bottom. In the QD the first bottom-locked layer can extend from 0.1 m to 100 m above the bottom. The second bottom-locked layer can be set to any height above the first within the overall limit of 127 m. If the operator does not wish to 'lock' the system to the minimum height of 0.1 m there is an off-set instruction of 0 to 1 m which can be used. In exceptionally shallow

conditions of 10 m, or less, the window looks for bottom signals within ± 50% of the last recorded depth. A data logger prints results on a record sheet, but, in addition the integrated signals from two selected 'layers' appear in analog form (mm deflection) on the echo-sounder paper record, adjacent to those echoes from which they are processed.

3.3.2 Biosonics DE1 120 Integrator

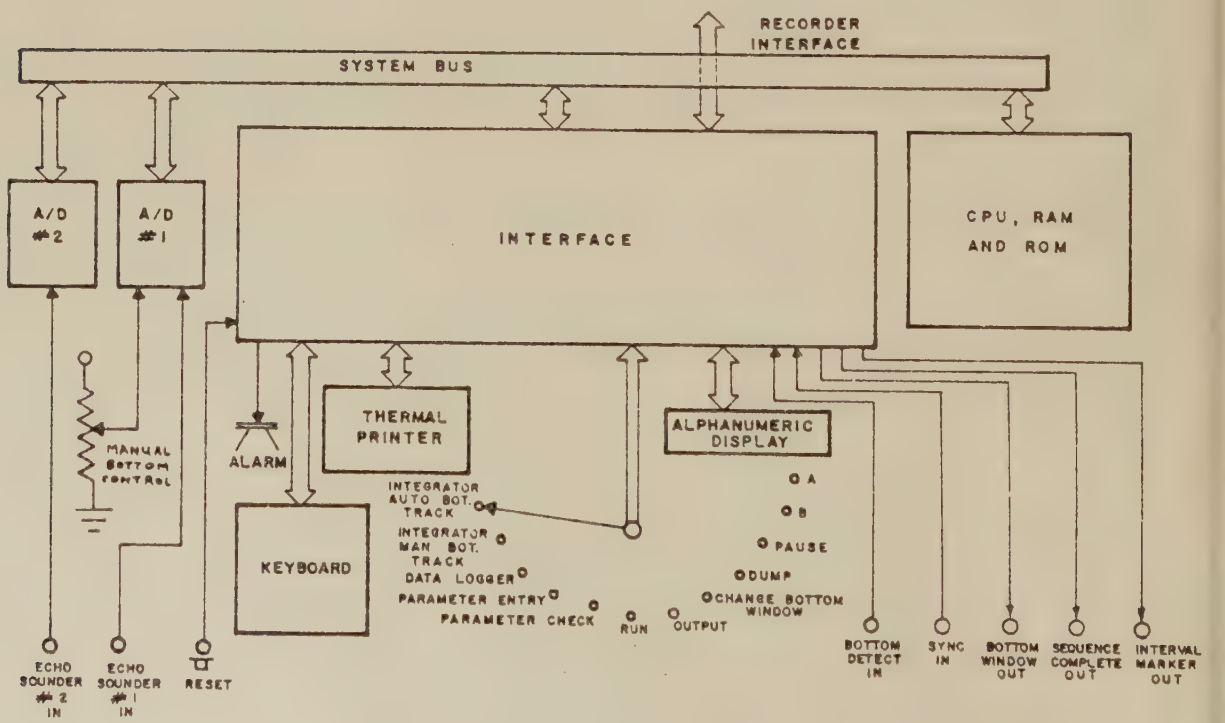
Figure 26

(a)



DIGITAL ECHO INTEGRATOR AS PART OF AN ACOUSTIC ASSESSMENT SYSTEM.

(b)



BLOCK DIAGRAM OF DIGITAL ECHO INTEGRATOR HARDWARE.

This is contained in one unit having a front panel mounted keyboard plus some analog controls. It can work in conjunction with echo-sounders operating over a wide range of frequencies but its input signals must be demodulated. In Figure 26(a) the integrator is shown as part of a complete acoustic survey system and Figure 26(b) is a block diagram of the echo-integrator hardware. Input signals of a maximum level of 7.5V pass through an ADC and are processed according to the internal program and the operators instructions.

The unit can be put into operation by pressing the RESET button which causes 'SELECT SYS MODE' to appear on the screen above the keyboard. One of the three system modes can then be selected by rotary switch.

1. Integrator Manual Bottom Tracking
2. Integrator Automatic " "
3. Data Logger

after which the MODE change key is pressed and the system is ready to accept parameters to be entered via the keyboard after prompts which appear on the screen. Most of the prompts appear with what is called a default value already entered for the parameter, if this value is correct, pressing the ENTER key will retain it and bring up the next prompt. Finally, when all parameters have been entered, 'SELECT MODE' appears, and the rotary switch turned to RUN followed by ENTER so that integration can begin.

Thirty depth intervals can be specified. The DE1 120 samples its input voltage every 134.2 μs, equal to 0.1 m depth increments for c = 1490 m/s. Sampled voltages above the threshold are converted to a 12 bit word by the ADC. Echo voltages appearing in each depth interval are squared and summed over the 0.1 m depth increments. After the specified number of transmissions a final sum-of-squares value is calculated for each depth interval and the values obtained are used to calculate fish density from the expression

$$\lambda_{xf} = Sxf.\dot{A}.Bx(P.Nx)^{-1}$$

where λ_{xf} = fish density for the (x) interval in $kg.m^{-3}$ or $fish.m^{-3}$ depending on units of the constant A

P = number of transmissions per sequence

Nx = number of 0.1 m increments per (x) interval

Bx = constant for TVG correction in (x) interval

$$A = \left[\pi.\tau.c.\sigma_{bs}.p_o^2.g_x^2.b_{a\nu}^2(\Theta)\right]^{-1}$$

where τ = pulse duration in seconds

c = speed of acoustic waves

σ_{bs} = average back-scattering cross-section of a single fish in $m^2.kg^{-1}$ or $m^2.fish^{-1}$

p_o = rms pressure of transmitted pulse in $\mu Pa.1m^{-1}$

g_x = transducer, cable, echo-sounder system gain in $V.\mu Pa^{-1}.1m^{-1}$

$b^2_{av}(\Theta)$ = means squared beam pattern weighting factor.

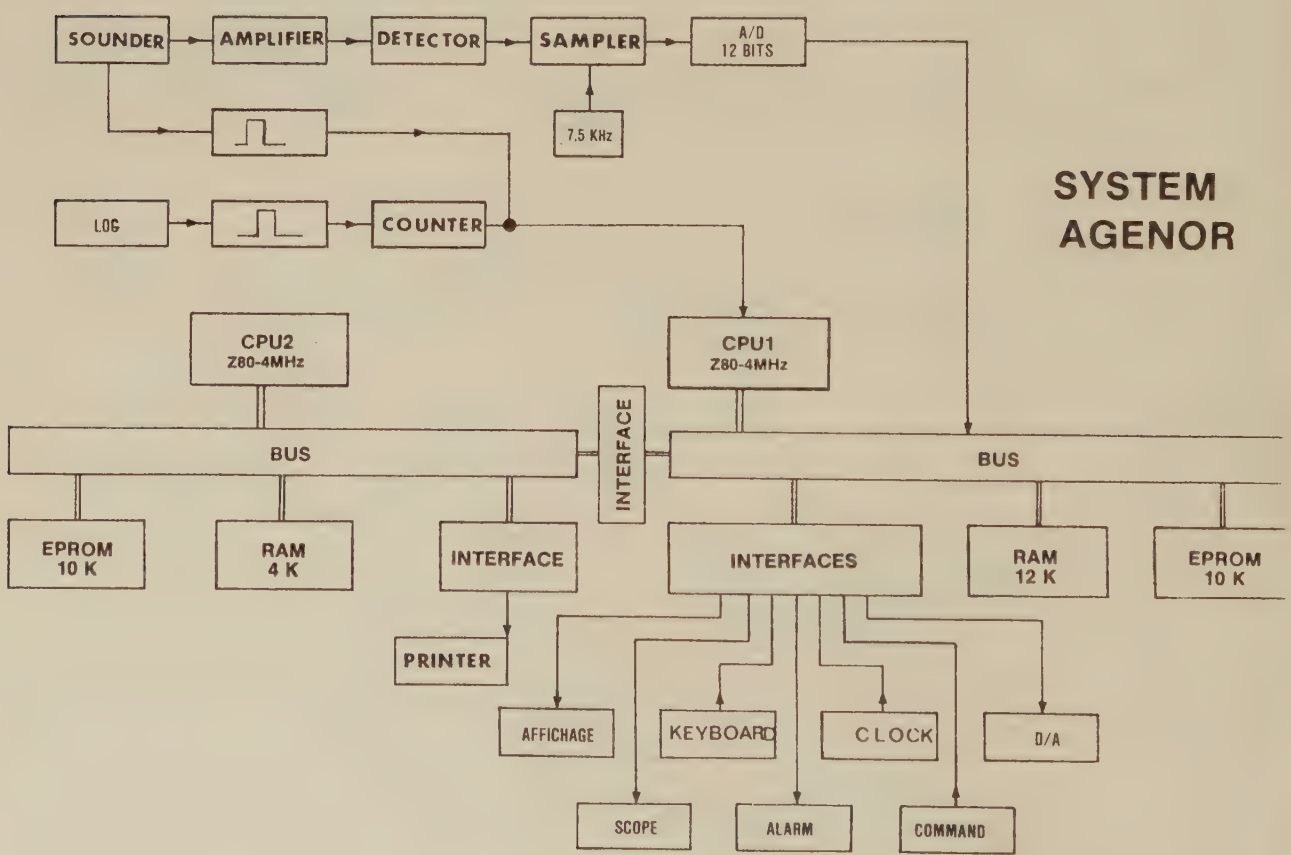
If a relative abundance survey only is being undertaken it is sufficient to let A = 1.

A paper printer forms part of the instrument from which the recorded data issues at the end of each sequence. These data are also available in ASC II (American Standard Code for Information Interchange) format at an RS232 output port for computer processing.

3.3.3 AGENOR Integrator

Also a self-contained unit, this integrator can operate from echo-sounders working at frequencies between 10 and 50 kHz. Demodulated analog signals from the echo-sounder

Figure 27



are sampled every 133.3 μs, equal to 0.1 m depth increments when c = 1550 m/s. An ADC changes the sampled voltages to 12 bit words.

System parameters relative to the survey are entered via the front panel keyboard prior to the start of a survey but they can be modified at any time although the effects do not occur until the next sequence. Modified parameters are printed out each time by the in-built printer and appear at the RS232 port. A block diagram of the system is shown in Figure 27.

When AGENOR is switched on the prompt "AGENOR VERS-0" appears and the operator selects the "CHGT PARAM" mode to enable the relevant parameters to be entered. The first line of parameters are displayed on the screen and also a cursor which can be incremented or decremented by keys for entry of new values. Key ↓ stores the completed current line after which the next line of parameters is shown.

There are 14 programmable parameters some of which are given below.

2, 3 and 4, Number of transmissions: Number of minutes per sequence: Number of 0.1 nautical miles per sequence

5. Threshold, referred to the ADC; is chosen by the operator looking at the demodulated signal.

6. Time interval for which automatic bottom tracking operates.

10. Acquisition mode 1: sequence stopped and new one started when number of transmission set in (2) is reached.

    2: Sequences are repeated when number of minutes (3) is reached.

    3: Sequence is stopped when log number (4) is reached.

11. Number of depth intervals (1 to 10) referred to the surface for which signals will be integrated.

12, 14 Constants A and B:

    A is an overall scale constant from a combination of factors including c and σ. It relates the sum of squared voltages to fish densities and has units of $kg.m^{-3}V^2$ or $fish.m^{-3}V^2$.

    B is a non-dimensional scale factor to correct for variations in the echo-sounder TVG.

There are also two depth intervals which are bottom-locked, they are called 11 and 12.

To start the system running, PAUSE is selected, the sequence number, the last automatic bottom value and the manual bottom value are then displayed. The bottom window is set over the bottom echo by the operator to obtain the initial value for automatic bottom tracking. When "ACQUISITION" is selected, data processing starts and at the end of each sequence data are printed out. The major part of the software calculates the average acoustic target density by unit surface (Rsj) or volume (Rvj) for each depth interval during a sequence of transmissions.

3.3.4 Furuno FQ Integrator

The Furuno FQ comprises a dual frequency echo-sounder and echo-integrator shown in the block diagram of Figure 27A. Echoes at each frequency are corrected by TVG before processing by an ADC and storage in the memory. A total of 3 bottom-locked and 9 transmission locked layers can be simultaneously integrated. One of each of these layers has the volume back-scattering strength printed out on the echo-sounder recording paper whilst the other ten values are listed on a printer output.

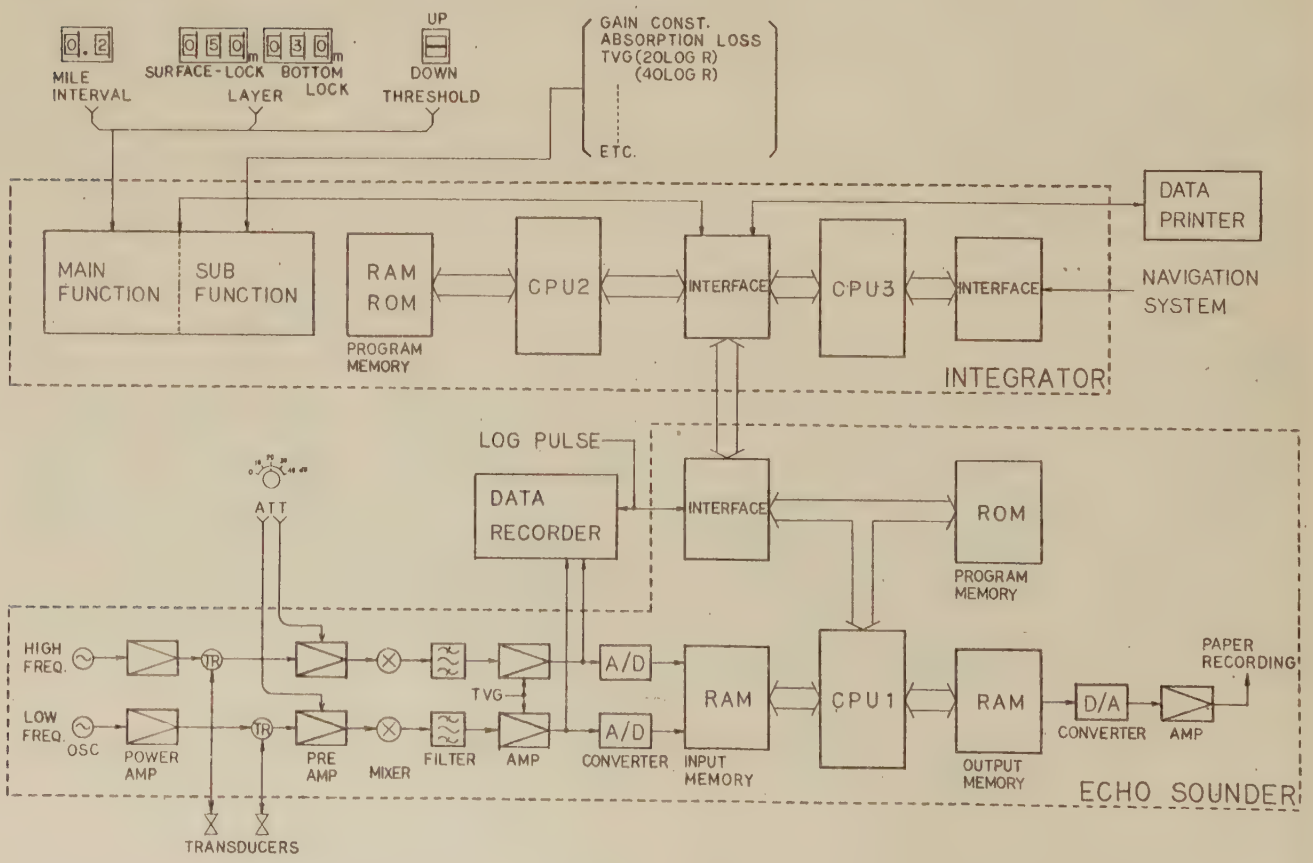
The rate of echo sampling is constant at 1024 times which on the 100 m range means every 98 mm and on the 500 m range every 490 mm. A vertical distribution of mean volume back-scattering strength (MVBS) in decibels with a dynamic range of 50 dB is registered in graphical form at every log marker position.

For the measurement of school aggregation density there are two possible methods. These are

i. from the vertical distribution graph read the MVBS at the centre of the school and add 10 logℓ/ℓG where ℓ is the log interval and ℓG is the horizontal length of the school shown on the recorder.

ii. select the aggregation average mode. Then the cross-sectional area of the school (SA) is calculated automatically within the integration layer wherein the school has occurred. 10 log ℓ (integration layer)/SA is then added to the MVBS for log interval ℓ.

Figure 27A



3.4 Test Instruments

As methods for the assessment of fish stocks by acoustic means have improved, so the need for greater precision in making the measurements has arisen and this is reflected in the accuracy with which the various parts of the equipment must perform their functions. Test equipment used to check these functions must be of known reliability and precision before being used on the calibration and measurement processes.

For any type of electronic equipment it is important to ensure that the correct supply and signal voltages are being applied. In this context, supply voltages relate both to the power supply of the ship and to the non-signal voltage levels which occur throughout the circuits making up the complete instrument. Development of test instruments has kept pace with the general trends in electronics so there is no difficulty in making accurate electrical measurements. It is mainly in the area of acoustic calibration that problems occur. These are due to the practical difficulties encountered in the alignment of standard targets, projectors and hydrophones in the acoustic beam and to the lack of stable characteristics of the latter devices.

Whatever type of measurement is made, it is vital that the readings are taken correctly. When making acoustic or electrical measurements, whether it be the small signal output of a hydrophone, or the output of a high-power transmitter, it is necessary to ensure that the values used for calculation are Root-Mean-Square (rms). However, it is much easier to read peak, or peak-to-peak values from the calibrated amplitude scale of an oscilloscope, so for convenience these values are taken and converted to rms (section 2.3).

3.4.1 Multimeters

i) Analogue

Instruments are called multi-meters if they are capable of measuring a number of functions by the connection of their input leads to different sets of terminals on the meter, or, more usually by turning a rotary switch. Modern multi-meters can measure AC or DC voltages and currents, often from microvolt (μV) or microamp (μA) levels, ie 10^{-6}, up to kilovolts (kV) i.e 10^{3} times, and to tens of amps. They also incorporate an ohmmeter to measure resistance of components or circuits, from 1 ohm (Ω) to perhaps 10 MΩ. Analogue types are so-called because they show the quantity being measured in relation to a scale.

The majority of analogue meters use moving coil construction with a thin pointer positioned over the scale. This has a disadvantage when reading the scale due to 'parallax error', caused by the observer being unable to judge when his line of sight is perpendicular (exactly 90°) to the scale and pointer. A slight angle to the perpendicular position results in a reading being too high, or too low. To assist in overcoming this difficulty all good quality meters are fitted with a strip of mirror embedded with the scale. If the observer looks at the reflection of the pointer in the mirror, then moves his head until the reflection is hidden by the pointer, he has reached the best position to read the scale accurately.

In order to get adequate resolution, the scale is made as long as possible, > 10 cm, and the ranges split into divisions which can be selected by a switch, eg 0-3V, 0-12V, 0-60V, etc, similarly for current, 0-12 μA, 0-6 mA etc. and resistance 0-2 kΩ, 0-200 kΩ etc. The electrical tolerance on these scales would typically be 2%, ie a reading should be to ±2% of the full-scale value.

An important factor with all analogue meters is the amount of loading they impose on the circuit being tested. Across the terminals of a meter there is a resistance due to the moving coil and the scaling components, this must be sufficiently high to avoid changing the actual value being measured. Typically, a good modern meter has a figure of between 20,000 Ω per Volt to 100,000 Ω per Volt, which means that each full scale value is multiplied by the resistance quoted in k Ω, ie 10V scale x 20 k Ω = 200 k Ω. For most purposes, other than some tuned and Field Effect Transistor (FET) circuits, 20 to 100 k Ω per volt is adequate.

When a fault has occurred in a circuit, as indicated by a low, or high voltage reading, the power is switched OFF and the ohm-meter section of the multi-meter is often used to investigate the circuit conditions. For this operation the meter provides a voltage at its terminals, which, when applied between particular points, will drive a current through the circuit proportional to the resistance encountered. This resistance, measured in ohms, is displayed in analogue or digital form by the meter.

Experience and knowledge of the circuit function is essential for correct interpretation of resistance readings. This is because many circuit elements, such as transistors and diodes, present a different resistance to the meter depending on the polarity of the applied voltage, ie the test leads, also, the windings of transformers have a different resistance to DC than to AC of a given frequency.

ii) Digital Multimeters (DMM)

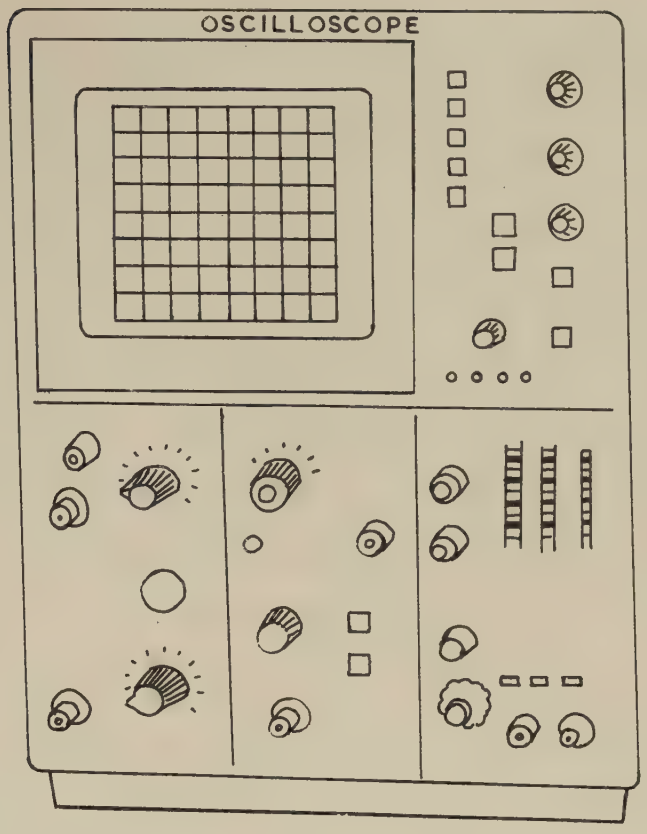
As the name implies, these meters display the measured quantity in decimal form by digits, either by Nixie tube, Light Emitting Diode (LED) or Liquid Crystal Display (LCD). They are designed with a very high input impedance of 10 M Ω to avoid the circuit loading problem inherent with most analogue meters. The accuracy on DC voltage is normally ± 0.1% of the reading, ± 1 digit, and on AC voltages and DC currents is 0.75% of the reading ± 1 digit.

3.4.2 Oscilloscopes

Very little work can be pursued on modern electronic equipment without the use of an oscilloscope. An oscilloscope is an instrument based on the ability of a cathode-ray tube (CRT) to display oscillatory voltages. It does this by deflecting an electron beam, directed at a fluorescent screen, simultaneously in two mutually perpendicular planes. When DC coupled, oscilloscopes can also measure steady voltages. The detailed functioning of a CRT is beyond the scope of this manual.

Figure 28

position
calibrate
level
trigger
focus
vertical
horizontal
auto
time/cm
volt/cm
persistence
delay
polarity



Despite a multiplicity of controls (see Figure 28), the oscilloscope has a basically simple function which is to display, for the purpose of measurement, the form of voltage variation in electronic circuits against time (their waveform). Figure 3 shows a sine wave in terms of its peak-to-peak voltages related to angle. The rate of change of angle is of course proportional to frequency. It is the purpose of an oscilloscope to measure the variation of waveform over a very wide range of frequencies and voltages.

The primary controls of an oscilloscope are, TIMEBASE, usually calibrated in micro-seconds per cm (μs/cm), milliseconds per cm (ms/cm), seconds per cm (s/cm) and VOLTAGE. Voltage calibration ranges from microvolts per cm (μV/cm), millivolts per cm (mV/cm), to Volts per cm (V/cm). In some cases the calibration graticule may be less than 1 cm, then the marking will be μs/division etc. Other controls are concerned with aspects of the waveform presentation rather than the fundamentals of the waveform itself. However, unless the user is able to control the presentation of a waveform, it will appear in a form unrecognisable to the human eye. One of the most important controls, and the one which is most effective in 'stopping' or 'holding' the waveform is the TRIGGER.

It is not unusual for the TRIGGER function to be divided amongst a number of knobs or push-buttons. Many oscilloscopes are constructed in modular form with separate plug-in modules for amplifiers, timebases, and triggering facilities, which might contain up to 20 front panel controls. This apparent over-complication is due to the need for the 'holding', or 'synchronising' of waveforms having different polarity, amplitude, frequency and repetition rate, and the requirement to examine certain parts of the waveform, e.g. to compare it with another waveform simultaneously, or sequentially and so on.

DELAY: This feature normally employs two timebases, one of which is called the delaying 'sweep'. A typical operation might involve the operator selecting, by means of the delaying sweep, a particular delay time. When this is reached, the second (delayed) timebase starts, and runs at perhaps ten times the speed of the first, thereby giving greater resolution of the selected portion of the waveform. More than one trace, or beam, is useful with this function so that the expanded portion can be compared with the whole waveform.

POSITION: There are two oscilloscope controls for precise positioning of the trace, horizontally (the time axis, X) and vertically (the voltage axis, Y) i.e. the waveform can be aligned in both X and Y planes with the scaled graticule. Vertical position controls are usually attached to an amplifier module, whilst the horizontal position control is often associated with the timebase module.

C.R.T. CONTROL: Quality of trace is determined by the setting of controls for brilliance, focus and astigmatism. Brilliance, or intensity is a control to be carefully used, because excessive brightness can result in burning the phospher on the screen. Focus sharpens the trace, enabling detail to be seen and making measurements easier, providing that the (often pre-set) astigmatism controls are adjusted to their optimum positions (these are used to obtain the 'roundest' spot from the electron beam). Most oscilloscopes have a control which gives variable illumination to the graticule allowing the scale to be easily read, or photographed.

DUAL-BEAM/DUAL-TRACE: A dual-beam oscilloscope contains two independent deflection systems within the same CRT, it can therefore display two input signals simultaneously even if they are non-recurrent and of short duration. These oscilloscopes are not now generally available.

The dual-trace incorporates electronic switching to alternately connect two input signals to a single deflection system. This allows a better comparison to be made because only one timebase and one set of deflection plates are used. Recent developments allow as many as eight traces to be displayed.

STORAGE: Two forms of storage are now used, CRT and digital. Both allow accurate evaluation of slowly changing phenomena, but the CRT type is preferable for viewing quickly changing waveforms as in underwater acoustics. As the name indicates, CRT storage is within the tube, either on a mesh or a special phospher and the PERSISTENCE control allows the selection of gradation between the bright trace and the dark background and also controls the time for which a stored image can be retained.

Digital storage relies on waveform sampling, ie taking signal values at discrete time intervals, and quantising, which is transforming the value into a binary number before transferring it into a digital memory. This storage method gives crisp, clear displays for unlimited periods, it can suffer from aliasing i.e. the sample data pulse train does not accurately represent the input signal. Most digital storage oscilloscopes sample often enough to display a 'clean' waveform from echo-sounders if operators take care to set the sampling rate correctly to avoid aliasing.

PROBES: The probes, although plug-in devices, must be regarded as an essential part of an oscilloscope system. They are designed to prevent significant loading of the circuit under test and are usually selected on the basis of adequate frequency and voltage response. For voltage amplitude measurements the capacitance and resistance of a probe form a voltage divider with the circuit being tested. At echo-sounder frequencies the resistive component is of major importance and needs to be at least two orders of magnitude greater than the impedance at the circuit point being examined.

It is also possible to measure transmission current with oscilloscope probes, something which is likely to become of increasing importance as the need to ensure even greater precision in the measurement of acoustic parameters. Current probes have a different form of construction and method of connection, to voltage probes, for, whereas the latter are connected directly to the terminals of a circuit, the current probe is clipped over the wire through which the current is flowing, (ie there is no 'metallic' contact).

3.4.3 Signal Generators

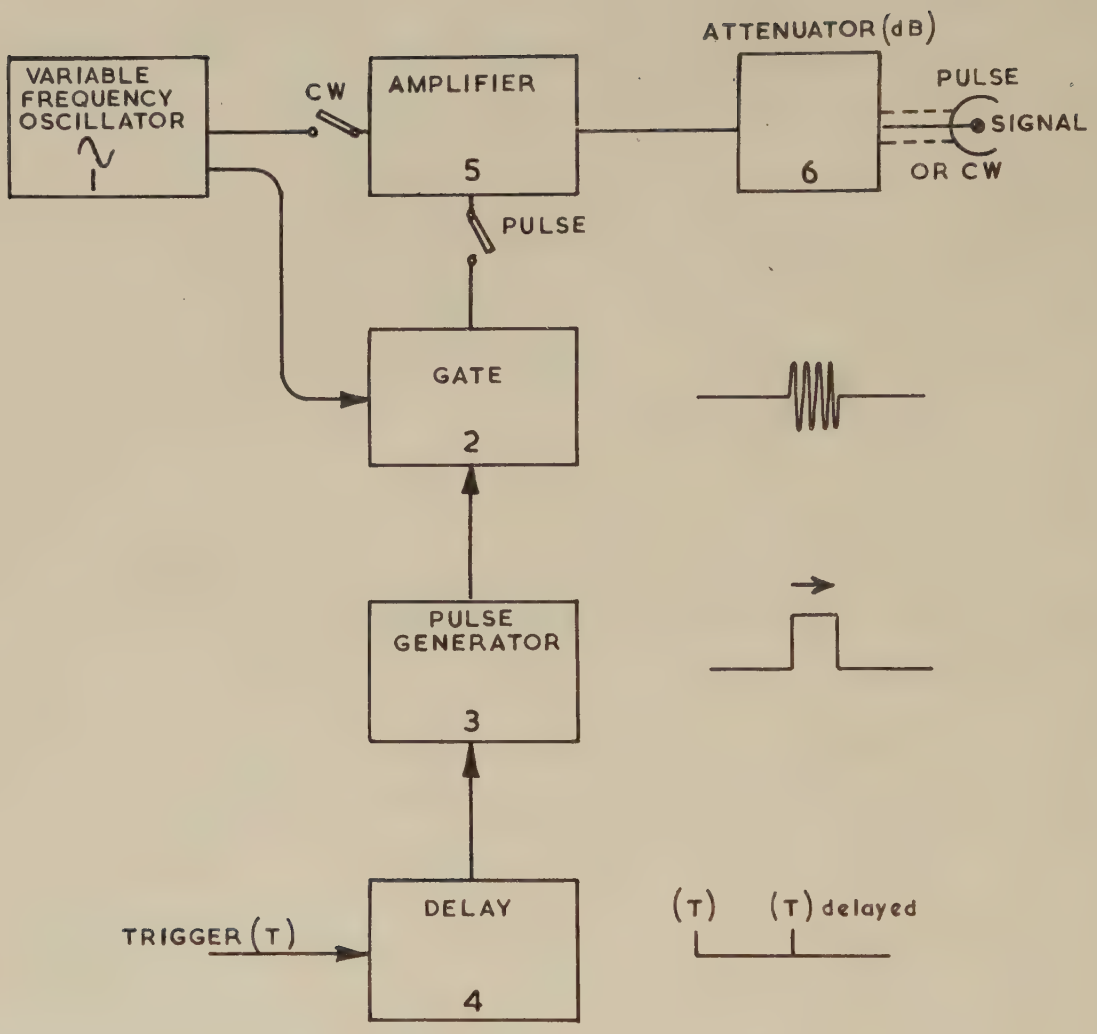
Although this instrument is a transmitter of electrical frequencies it differs from the echo-sounder transmitter in most respects excepting for the generation of frequencies. The signal generator provides signals (transmissions) accurately controlled in frequency and amplitude which can be varied over a wide band of frequencies and levels of voltage whilst remaining pure in waveform.

It is the purpose of a signal generator to provide the means of electrically calibrating receiving amplifiers in terms of their sensitivity, dynamic range and bandwidth. A wide range of precisely controlled ouput voltage level is necessary, preferably from $< 1\ \mu V$ to $> 10V$. The signal generator should be capable of producing at the echo-sounder frequency CW and pulses (bursts) of controlled variable duration, which, by means of a time delay (depth control) can be set anywhere in the full depth scale of the echo-sounder under test. Accuracy and stability are of prime importance.

Figure 29 illustrates the essential features of a signal generator. Block 1 is the oscillator which generates CW at the frequency selected by the switch (coarse range) and the tuning dial. This oscillator must have the properties of low harmonic distortion and high frequency stability. Its output is fed to an electronic gate, Block 2, controlled by the square waves from Block 3 for pulse mode, or, bypassed completely for CW mode. Block 3 has a control by which it is possible to vary pulse duration to simulate the transmitted pulse.

There are two modes of operation for block 3, 'free-run' and 'triggered'. In free run, the rate at which pulses are produced can be varied within limits. When in triggered mode, only one pulse occurs for each revolution of the recorder stylus, in response to the echo-sounder trigger pulse. However, the time (depth) at which it occurs can be set by the time delay control (block 4), initiated by the recorder trigger pulse.

Figure 29



BLOCK DIAGRAM OF A SIGNAL GENERATOR

The output of the gate is amplified (block 5), then fed to an attenuator (block 6), calibrated in voltage or dB. An essential feature of the attenuator is low output impedance so that signals can be injected into the transducer/receiver input circuits without adversely affecting them. When injecting signals, especially of μV level it is necessary to avoid introducing electrical interference to the circuit and a good method is to use an inductive form of coupling into one of the leads between the transducer and the receiver. Such an arrangement reduces the impedance introduced into the circuit, typically by 100 times, from say 0.1 Ω to 0.001 Ω.

Care must be taken to prevent direct coupling between the signal generator circuits and those of the receiver amplifier under test, or false measurements may result. It is

normally sufficient to ensure that the earthing arrangements for the two are correct and that the correct cable from the signal generator is used for connection to the receiver.

The signal generator should include fine frequency control of tuning, because of the relatively narrow bandwidth of receivers. However, the precise frequency to which the generator is tuned can best be obtained by use of a frequency counter. This instrument is discussed in section 3.4.4, it gives a direct digital reading of frequency when connected to a CW output. The importance of a frequency counter is best illustrated by considering a practical example.

An echo-sounder is tuned to the resonant frequency of its transducer, 38.75 kHz, and has a bandwidth of 2.2 kHz to the -3 dB points. By using a frequency counter it is easy to set the signal generator, first to 37.65 kHz (-1.1 kHz), then to the centre frequency, 38.75 kHz and lastly to 39.85 kHz (+1.1 kHz). It would be extremely difficult to achieve acceptable accuracy if an analogue dial or scale were used.

3.4.4 Electronic Counters

The type of electronic counter used in fisheries acoustics is one which can make a precise count, or measurement, of frequency. It gets its name because the measurement is made by counting the number of sinewaves which occur in a given period of time. This number is displayed digitally, usually in kHz. Frequency counters of this type have become sophisticated devices but are quite simple to use. Controls are limited to selection of the number of digits to be displayed, selection of the mode of operation (if timing and other measurements are possible) and the input level. The latter is particularly important in some of the older instruments because if the input level was set too low or too high readings were erratic.

It is difficult to use this form of counter to measure the frequency of a pulse transmission or echo. Manufacturers normally provide a CW output of the transmitter oscillator where this can be done and signal generators can be switched into CW for the same purpose.

3.4.5 Hydrophones

These are the sensor devices, defined as transducers, which provide electrical signals in response to waterborne acoustic waves. When a hydrophone is placed in the acoustic field (beam) of an echo-sounder transducer, it responds to the pressure fluctuations and produces a proportional voltage across its terminals. A conversion factor is supplied by the hydrophone manufacturers which enables the voltage to be related to acoustic pressure at the frequency being used. This is usually in the form of the number of decibels relative to one volt which can be measured for each micropascal of pressure, dB/1V/1μPa. In the past it was given as dB/1V/1μb) but the microbar (μb) has been superseded and 100 dB must be added to μb figures to bring them to μPa. For example, a typical figure of -75 dB/1V/1μb when converted to the SI unit is -175 dB/1V/1μPa.

Modern calibration hydrophones are designed to have an omni-directional response in one plane, but often have some undesirable directionality in the other. They are made

from physically small electrostrictive elements encased in acoustically transparent, but watertight material. Usually they have a wide frequency band response but some change in the characteristics can occur with change of temperature. Calibration normally includes the length of connecting cable supplied. This cable must neither be shortened, nor lengthened, unless proper allowance can be made for such changes.

3.4.6 Projectors

A projector is a transducer which, when supplied with electrical power produces pressure waves corresponding to the frequency at which it is driven. Projectors for calibration purposes normally have an omni-directional response over a wide band of frequencies. The same transducer can also be used as a hydrophone, if it has reversible characteristics. Care must be taken to avoid overloading when operating in the projector mode because this can strain the material and therefore change the hydrophone calibration. The projector calibration factor is related to a given electrical driving power for which the acoustic pressure can be calculated, usually in the form dB/1μPa/1V. A typical figure might be 228 dB/1μPa/1V. If the calibration is given in terms of the now discontinued unit it would be 128 dB/1μb/1V.

3.4.7 Calibration of Test Instruments

The most important factors in maintaining calibration, and a good performance from any item of test equipment are, care in using it, in handling it, and particularly in transporting it. Before using any test instruments, it is necessary to make some simple checks to be sure that they are functioning properly. Failure to do this may result in much time being wasted, through both the recording of incorrect data and attempts to find non-existent faults in survey equipment.

Tests on multimeters are quite simple. The ohm-meter ranges can be checked to see if the pointer (or digits in a digital meter) can be zeroed. If not, the most likely reasons are that the battery is low, or, the leads are broken or making bad contact at the terminals, matters which can be rectified easily. The accuracy can then be roughly checked by measuring a few close tolerance resistors whose values are chosen to check the instrument at various points throughout the scales.

Checking the function and calibration of the voltmeter sections may be more difficult. Direct current (DC) scales can be roughly checked on known dry battery voltages or, more accurately on laboratory or bench type power units. However, if the instrument is of good quality and it has been well treated, (ie not overloaded, dropped, or subjected to severe vibration in the case of moving coil meters), it is unlikely that its accuracy will have deteriorated. Current measuring scales can be checked by switching to the highest current scale, then inserting the meter in series with a circuit of known potential difference and resistance so that the current which should be indicated can be calculated. Starting any measurement using the highest range of voltage and current is a sensible precaution.

For an alternating current meter it is necessary to be sure what the scale is indicating. Normally calibration is in terms of the rms value of a true sine wave (see 2.3).

Deviations from a pure sinewave, (distortion) will cause some error in the reading by an amount depending on the 'form factor'. This is only obtainable by waveform analysis. Observation of the waveform with an oscilloscope will indicate any obvious distortion which might affect the result.

Once the electronic equipment has been thoroughly checked and calibrated, the acoustic calibration can be considered. The various methods of achieving this are discussed in chapter 7.

4. FORMING THE ACOUSTIC EQUATIONS

This section of the manual describes the simplest practical situations for the use of parameters linked by the acoustic equations (formerly known as the sonar equations). These parameters relate to the water as a transmission medium for acoustic waves: to fish as acoustic targets in this medium and to the characteristics of the acoustic system.

It is a law of physics that energy can be neither gained, nor lost. This applies to acoustic waves as well as all other forms of energy. The acoustic equations help us to balance the quantities of acoustic energy transmitted and received, rather similar to the way a financial statement should balance. If the separate terms of the equation are accurate we can estimate fish biomass. The effectiveness of acoustic systems can be limited by the sea's own natural background of acoustic energy (noise), which is increased by transfer of energy from the wind, fast currents over certain types of seabed, Harden Jones and Mitson (1982), or from rain acting on the surface. It is necessary to know and understand the units of measurement, their quantities and the relationships which describe the parameters in the acoustic equation to manipulate them correctly.

In the water we are concerned primarily with transmitted acoustic source level measured in dB/1μPa/1m, and in received echo level in dB/μPa, but familiarity with the concepts of acoustic power (WA, Watts) and intensity I, is useful. To put energy into, and also to take it out of the water there is the energy converter, the transducer, discussed in 3.1.3. It is difficult to make actual acoustic measurements, so the electrical transmitted and received voltages and powers are used.

Echo-sounders and echo-integrators are calibrated in decibels, the use of which is standard for equipment in acoustic survey systems and in the acoustic equation. To see how these are used in calculations with acoustic energy we start by considering a transducer placed in the water. For our purpose the power is concentrated into a beam directed downwards.

4.1 Power and Source Level

We have seen how electrical power, when applied to a transducer, becomes acoustic power, or intensity. This section relates the factors which determine the acoustic intensity, or source level (SL) produced by a transducer.

Source Level is defined as

$$10 \log (\text{intensity of source/reference intensity}) \quad \ldots\ldots\ldots\ldots\ldots (26)$$

where the reference intensity is that of a wave of rms pressure 1μPa.

Power input (Pe), to the transducer is in the form of an electrical pulse and is measured across the cable connections from the transmitter to the transducer.

$$Pe = V_{rms}^{2} R^{-1} \quad \text{Watts}$$

No transducer is 100% efficient in converting electrical to acoustic power, or vice versa. To find the acoustic power output (WA) for a given electrical power input it is necessary to know the transducer efficiency, (η) see 3.1.3. Supposing η is 70%, and the electrical input is measured as 1000 W, then the acoustic power (WA) is

$$WA = \eta Pe$$
$$= (70 \div 100) \times 1000 = 700 \text{ Watts.}$$

What is needed for our acoustic equation calculations, is the SL which results from this acoustic power.

SL is expressed as

$$SL = 170.8 + 10 \log WA + DI \quad dB/1\mu Pa/1m \qquad \ldots\ldots\ldots\ldots\ldots (27)$$

i.e. reference 1μPascal at 1 metre on the axis; a one metre reference distance from the transducer face is normal.

170.8 is a constant for converting acoustic power to source level (see Urick (1975) P67).

DI is the directivity index, section 3.1.3.

From this information and using a figure of 23 dB for DI we can calculate SL at the reference distance of 1 m.

$$SL = 170.8 + 10 \log WA + DI$$
$$= 170.8 + 28.45 + 23 = 222.2 \text{ dB}/1\mu Pa/1m$$

This is the axial transmitted acoustic intensity at the reference distance of one metre from the transducer face. Although source level can be calculated in this way it is not a satisfactory substitute for a direct or indirectly measured value obtained during acoustic calibration, because the electrical waveform is often distorted and Pe cannot always be measured accurately. Having obtained a figure for SL we can apply the particular laws of propagation for acoustic waves and calculate the intensity for any given distance.

4.2 Decrease of Intensity with Distance

If an acoustic beam was infinitely narrow it would suffer no loss except for absorption. But when practical beams are propagated through water they spread so that the power WA covers a continually increasing area as distance from the source increases. We saw in 2.5 that acoustic intensity at any point is equal to power divided by area

$$I = WA \div \text{Area}$$

Knowing how the area increases with distance from the source we can calculate how intensity decreases with increasing distance. If a transducer radiated waves equally in all directions the waves would spread spherically from it. Even though we use transducers which confine the acoustic waves into a beam, the wavefront is still spherical ie it is a small part of the surface of an expanding sphere, see Figure 30.

From geometry we know that the area of the surface of a sphere of radius a is $4\pi a^2$. The radius of the sphere from which our beam is taken is the distance from the transducer

to the wavefront. Therefore the acoustic intensity on the axis of the beam decreases in proportion to the distance squared.

Power = Intensity x Area

" $= 4\pi d_1^2 I_1 = 4\pi d_2^2 I_2$ so taking the ratio

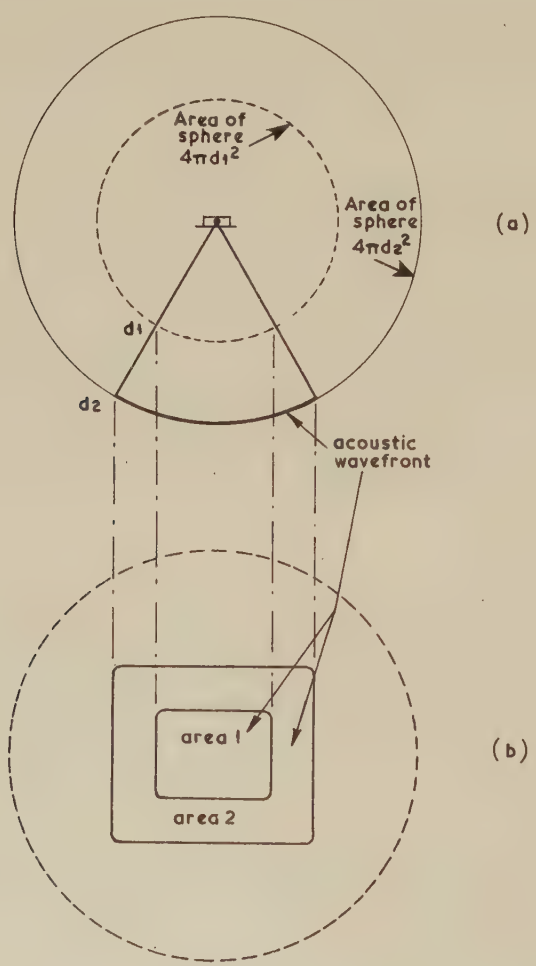
$$\frac{4\pi d_1^2 I_1}{4\pi d_2^2 I_2} = 1, \qquad \frac{I_1}{I_2} = \frac{d_2^2}{d_1^2} = \left[\frac{d_2}{d_1}\right]^2$$

but the distance d_1 is the reference distance of 1 m
so $I_1/I_2 = d_2^2$
in decibel notation

$$10 \log I_1/I_2 = 10 \log d_2^2 = 20 \log d_2$$

d_2 represents any distance relative to the reference and is conventionally called R, the range from a source to a given distance.

Figure 30



Thus the normal expression is 20 log R and this is one component of the transmission loss factor TL. Although the term, range R, is more suited to the horizontally directed beam of sonar, it is useful in echo-sounding also. This is because all targets present at the same instant over the spherical surface of the wavefront are at the same range but they are not at the same depth. It will be seen later how these two factors occur in different situations but for the purpose of the acoustic equation, R will now be used throughout this manual.

So . . $TL_1 = 20 \log R$

Another component of transmission loss, is the absorption (α), discussed in 2.6, this follows a linear law with distance so it is added to the expression above in the form αR, and the full transmission loss TL is

$$TL = 20 \log R + \alpha R \qquad \ldots\ldots\ldots\ldots\ldots\ldots (28)$$

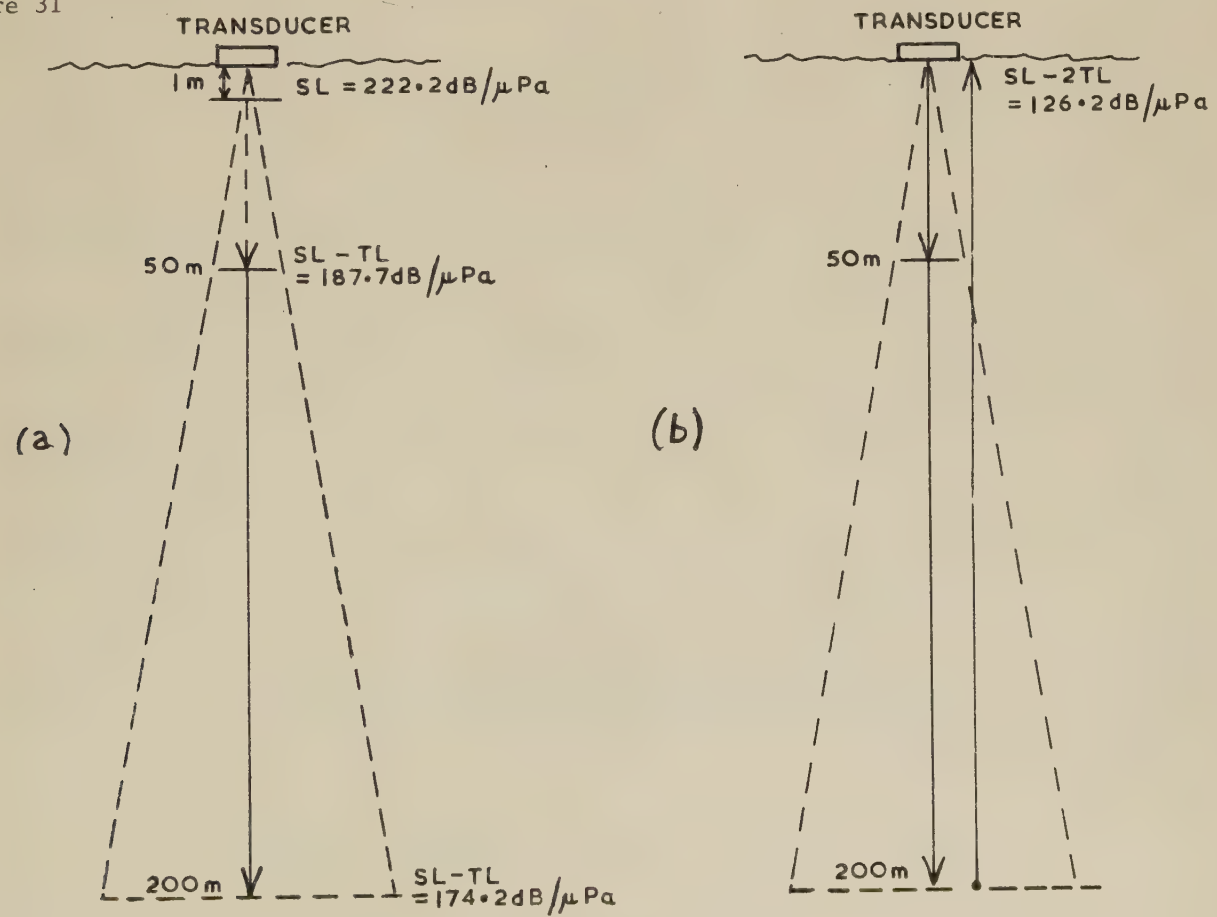
Using (28) we can calculate the intensity at a range of R metres from the transducer source. Let R = 50 m and α = 10 dB/km.

SL-TL = 222.2 - (20 log50 + 10 x 50 ÷ 1000)

222.2 - (34 + 0.5) = 187.7 dB/1μPa

At 200 m SL-TL = 222.2 - (46 + 2) = 174.2 dB/1μPa (see Figure 31(a) below.

Figure 31



Thus the intensity is reduced most significantly by the spherical spreading or 'geometrical' loss, 20 log R, but as the range increases α becomes important. Because α

increases greatly with frequency, its effect must be considered at relatively short ranges when high frequencies are used.

The one-way transmission loss is used above, but in order to obtain an 'echo-sounding' the echo must return in approximately the same direction as the transmitted pulse if it is to be received. The one-way transmission loss occurs over the distance travelled by the transmitted pulse and this added to the distance travelled by the echo, gives the two-way transmission loss = 2TL. For the present purpose we assume that all the acoustic intensity at 200 m is returned towards the transducer.

$$\begin{aligned} SL-2TL &= 222.2 - 2(20 \log R + \alpha R) \\ &= 222.2 - (40 \log R + 2\alpha R) \\ &= 222.2 - 2(48) \qquad = 126.2 \text{ dB}/\mu\text{Pa} \end{aligned}$$

as shown in Figure 31(b).

This is the intensity or echo level (EL) received at the transducer face after the acoustic waves have travelled a total of 400 m on the axis of the beam.

$$EL = SL-2TL \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (29)$$

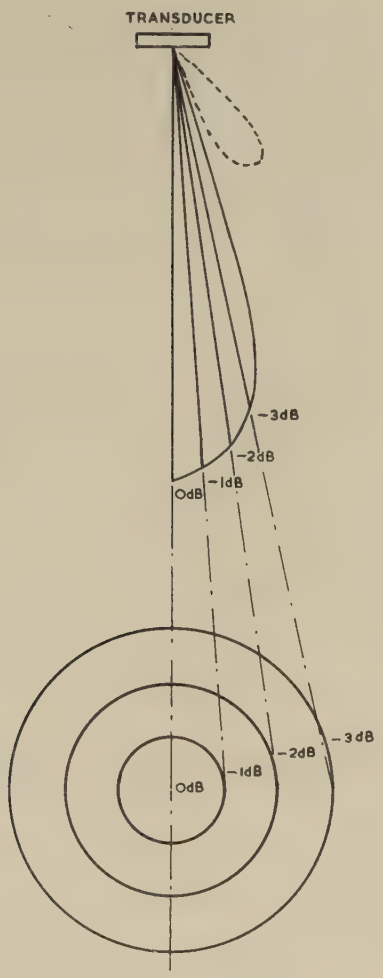
Having seen how intensity decreases with range we now consider how it varies across the beam.

4.3 Variation of Intensity across the Beam

In 4.2 we examined the decrease of intensity with range from the transducer along the axis of the beam. As the beam gets wider with increasing range, so the wavefront area increases. The decrease in intensity with range can be calculated as shown in 4.2 and compensation applied by varying the amplification of received signals according to their range (by time varied gain i.e. TVG).

This would be quite sufficient if the intensity was constant over the area of the beam at any given depth. But, we saw in 3.1.3 that as the angle from the axis increases, so does the intensity decrease. Thus if we consider the area of the beam at a certain range, the acoustic intensity on the beam axis will be equal to SL - TL. But, at the reference angle from the axis it will be SL - TL - 3 dB. There is a gradual decrease in intensity from the axis to the -3 dB reference level which is illustrated by zones in Figure 32. These zones indicate what is probably the most difficult problem in fisheries acoustics, i.e. we do not know which zone fish are in at any given instant so it is impossible to make direct quantitative measurements with a simple echo-sounder. The effect of the beam pattern can be removed by a number of techniques but there is one in particular which is most widely used, Urick (1975), it forms the basis of section 4.6.

Figure 32



4.4 Single Fish as Acoustic Targets

In 2.8 we saw some of the factors which determine the amount of acoustic energy reflected from fish and its variability. Here we are concerned with the most simplistic way in which single fish targets can enter the acoustic equation. It is shown in 4.2 that the echo level at the transducer when all acoustic energy reaching range R is reflected is

$$EL = SL - 2TL$$

or $$EL = SL - (40 \log R + 2\alpha R)$$

But we are normally concerned with small objects which intercept only a small proportion of the acoustic energy. Figure 33 illustrates this, and that

$$TS = 10 \log \frac{\text{reflected intensity at 1 m from the fish}}{\text{incident intensity which strikes the fish}} \quad \ldots\ldots\ldots\ldots (30)$$

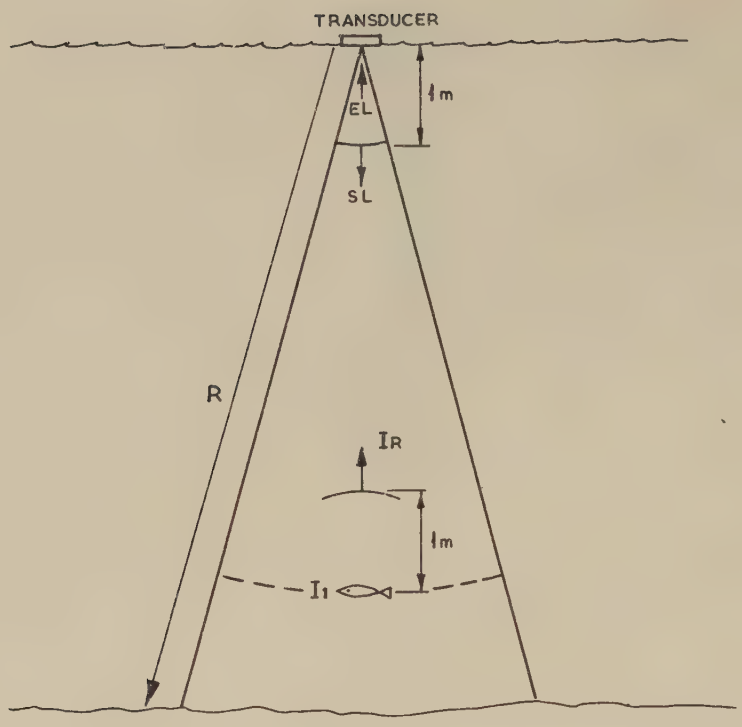
If all incident energy was reflected

$$I_R/I_1 = \frac{\text{reflected intensity}}{\text{incident intensity}} = 1 \text{ and } 10 \log 1 = 0 \text{ dB} \quad TS$$

so the echo level would remain unchanged by adding this value of TS.

$$EL = SL - 2TL + 0$$

Figure 33



A fish returning a small proportion of the energy has a much lower TS. Supposing the ratio of I_R/I_0 = 1/1000, i.e. the amount reflected is 1000 times less than the incident intensity, then

$$TS = 10 \log 1/1000 = -30 \text{ dB}$$

In a practical situation the EL would be received and we would want to extract TS, given the other factors

$$TS = EL + 2(20 \log R + \alpha R) - SL$$

$$TS = EL + 2TL - SL$$

Using the figures from 4.2, assuming EL = 96.2 dB/1μPa when R = 200 m and α = 10 dB/km

$$TS = 96.2 + (92 + 4) - 222.2 = -30 \text{ dB}.$$

Of course this applies only to the axis of the beam. Note that 40 logR occurs above, it is always associated with single targets

$$2TL = 40 \log R + 2\alpha R \qquad \ldots\ldots\ldots\ldots\ldots (31)$$

The target strength of a single fish has been defined, but this cannot be directly applied to large numbers of fish. Instead a figure of mean target strength for a mean length of a particular species, is related to weight so that a figure in dB/kg is obtained for use in the equation to determine biomass. Data are often available from which weight/length relationships can be calculated, these are in the form $W = kL^x$

where W = weight

k = species related constant

L = length

x is ≈ 3, i.e. weight is proportional to the length cubed, (also species related).

4.5 Fish Schools as Simple Acoustic Targets

In 4.4 we assumed that one static, rigid fish reflected a 1/1000 part of the intensity incident upon it. The TS of this fish was found to be -30 dB. With similar reasoning we might say that 1000 fish each of the same TS would reflect all incident acoustic energy if they were filling the beam at precisely the same range. If the school TS is called TS_s the relationship is

$$TS_s = 10 \log N + TS \qquad \ldots\ldots\ldots\ldots\ldots (32)$$

where N is the number of fish, each of target strength TS

$TS_s = 30 + (-30) = 0$ dB.

In practise the target strength of schools is only useful when horizontally directed sonar beams are used to measure discrete schools. For the present form of acoustic equation we need a term to describe the amount of energy back-scattered from the school or layer to the echo-sounder transducer. This is known as volume reverberation which depends upon a ratio called scattering strength, in decibel terms it is

$$S_V = 10 \log \frac{\text{back-scattered intensity from unit volume at 1 m distance}}{\text{incident intensity}}$$

The term EL has previously been used for the echo received at the transducer but when considering reverberation the analogous term RL, refers to the equivalent plane-wave reverberation level. It is defined as the level of an axially incident plane wave which produces the same transducer output as the reverberation. For general use of RL some assumptions must be made about the scatterers (fish) comprising the scattering layer.

1. The acoustic wave propagation must be in a straight line and the spreading loss taken into account.
2. Fish must be distributed with equal probability throughout the volume contained by half the pulse length at any given range.
3. There must be an absence of multiple scattering. (see Chapter 5).

Point 2 is especially relevant to the acoustic equation because it affects the transmission loss TL. This is because one way TL is 20 log R, i.e. when range increases by 2 times, the area of the wavefront increases by 2^2. Thus the number of targets intercepted by the beam increases in the same proportion as the TL which effectively cancels out the TL in one direction. This is the second form of the transmission loss equation, used for schools, or layers spread across the beam. Note that α is still a two-way loss.

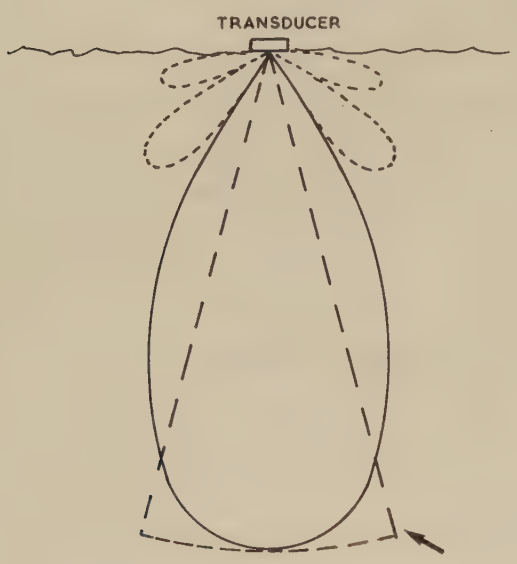
$$TL_2 = 20 \log R + 2\alpha R \qquad \ldots\ldots\ldots\ldots\ldots (33)$$

Volume reverberation is discussed in section 6.1 based on Urick (1975).

4.6 An Equivalent Transducer Beam

When the acoustic beam passes through a school or a layer of fish, fish spread across this beam at a given time and range. The reverberation level (RL) received at the transducer face is proportional to the number of fish and to their distribution across the beam. Even if they were all of the same TS, a small number would be in the 0 to -1 dB to -2 dB, and more still in the -2 dB to -3 dB zone (see Figure 32) the total RL would be much less than if the transmitted intensity were constant across the beam.

Figure 34



The solution is to calculate an equivalent beam. Within this ideal beam there is unity response, but outside, the response is zero. Figure 34 shows the comparison diagrammatically. Preferably measured parameters of the actual transducer are used in the calculation, which takes into account both transmission and reception i.e. two-way pattern, but a different formula is used for different shapes of the transducer face.

In logarithmic terms the formulae are

1. Circular transducers

$$10 \log \Psi = 20 \log(\lambda/2\pi a) + 7.7 \quad \text{dB/Steradian} \qquad \text{.....(34)}$$

where λ = wavelength (m)

a = radius of the transducer active face

$a > 2\lambda$

2. Rectangular face transducer

$$10 \log \Psi = 10 \log(\lambda^2/4\pi ab) + 7.4 \quad \text{dB/Steradian} \qquad \text{..... (35)}$$

where λ = wavelength (m)

a = length of one side of the active face (m)

b = length of the other face (m)

$a, b \gg \lambda$

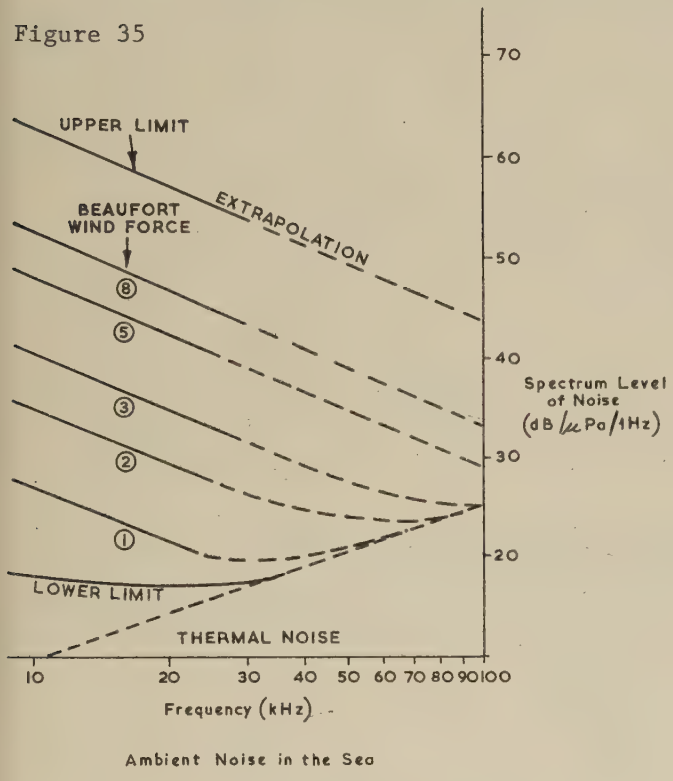
These formulae are taken from p.217 of Urick (1975) and assume normal transducer characteristics, e.g. a properly formed main beam and the number, volume and sensitivity of the sidelobes. For accuracy a detailed three-dimensional measurement of the actual beam pattern is needed from which an equivalent solid angle can be calculated. Special facilities are needed for this purpose.

Schools of fish intercept and re-radiate some of the acoustic energy in the echo-sounder pulse. This re-radiation is called scattering and the sum of the scattering in a given volume of water is called the volume reverberation.

Because the scattering of interest goes back in the direction of the echo-sounder transducer it is often specified as 'back-scattering'. Reverberation is due to those fish within the 'ideal' beam contained in the volume of the equivalent beam Ψ, the pulse duration τ, and the range R.

4.7 Noise Level

Figure 35



Ambient Noise in the Sea

Frequency (kHz)

Ambient Noise in the Sea

The limit to the detection of fish in the sea is noise. In the acoustic equation the noise level NL at the face of the receiving transducer is defined as

NL = 10 log (noise intensity/reference intensity) ..... (36)

where the reference intensity is that of a wave of rms pressure 1μPa.

Noise can arise from many sources, see 9.3, the present purpose is to consider it in relation to the acoustic equations.

Figure 35 shows how the ambient noise level varies with wind strength and sea-state, but note that this noise is given as spectrum level (SPL), which refers to the energy of an acoustic wave in a frequency band 1 Hz wide. The actual noise can then be calculated for any bandwidth and it emphasises that, the greater the bandwidth of a system, the more noise is received, regardless of its origin. The noise level affecting an echo-sounder of bandwidth BW is approximated by

$$BL = SPL + 10 \log BW \quad \text{..... (37)}$$

where BL = band-level of noise (dB/μPa)

SPL = spectrum level of noise (dB/1μPa/1Hz)

BW = bandwidth of the receiving system (Hz)

This approximation holds if the bandwidth is not too great, a condition met by present-day fisheries echo-sounders. It is based on adding together the intensities in the adjacent 1 Hz bands across the bandwidth.

To see the extent to which a given wind force or sea-state will affect an echo-sounder we take the spectrum level at the frequency of operation, eg 40 kHz. From Figure 35 the SPL at this frequency for wind force 3 is 30 dB/1μPa/1Hz. An echo-sounder with a bandwidth of 3 kHz would therefore receive a total noise level from this source of

$$BL = 30 + 10 \log 3000 = 64.8 \text{ dB/1}\mu\text{Pa}$$

To appreciate the practical significance of this noise level it must be compared to signals we wish to detect by expressing it in the form of voltage received across the transducer terminals (VRT).

Assuming a transducer with a receiving response (SRT) of -185 dB/1Volt/1μPa,

$$VRT = BL + SRT$$
$$= 64.8 + (-185) = -120.2 \text{ dB/1Volt}$$
$$\approx 0.98 \ \mu V$$

(note the BL is effectively EL or RL).

If the wind increased to Beaufort Scale force 8 the SPL = 42 dB/1μPa/1Hz so that

$$BL = 76.8 \text{ dB/1}\mu\text{Pa}$$
$$VRT = 76.8 + (-185) = -108.2 \text{ dB/1Volt}$$
$$= 3.9 \ \mu V \text{ of noise.}$$

Maximum sensitivity of an echo-sounder is likely to be 1μV or even less, hence this level of noise could restrict the detection of fish. However for quantitative measurements a signal-to-noise ratio of 10-20 dB is necessary so maximum sensitivity cannot be used always.

Using the equations discussed in section 4, we can calculate the signal voltage from a fish of known TS at a given depth and compare it to the noise. Assuming that an echo-sounder has an SL of 216 dB/1μPa/1m and it is required to detect a fish of TS = -45 dB at a range of 200 m. Let $\alpha \approx 8.7$ dB/km

$$EL = 216 - 2(20 \log 200 + (8.7 \times 200)/1000) + (-45)$$
$$216 - 95.5 - 45 = 75.5 \text{ dB/1}\mu\text{Pa}$$
$$VRT = 75.5 + (-185) = -109.5 \text{ dB/1Volt}$$
$$= \text{Antilog} - 109.5/20 = 3.35 \ \mu V \text{ of signal}$$

The fish signal is 0.55 μV less than the average noise and cannot be detected.

Wind-induced noise has been used above to illustrate how noise may be included in the acoustic equations but there are other sources of noise (see section 9.3).

There is rarely a provision for noise to be monitored automatically during a survey. A deterioration in weather conditions often warns the operator before noise appears on the record, although if the system is operating near its maximum range capability the margin between an acceptable and an unacceptable noise level is small. An average level for noise can be taken from Figure 35 for a given wind force, but because of the variability of the wind this may not be adequate for very long. Rain causes a very significant increase in local noise levels and noise transients can occur when a ship slams into a heavy swell.

The speed at which a survey can be run often depends on the noise from the propeller, a factor with a high rate of change with speed, so it may be necessary to choose a survey speed well below that which causes noise to be integrated.

Threshold controls are provided on most integrators to minimise the effects of noise but they tend to bias the results so should never be used unless absolutely essential. Either way there is no direct insertion of a noise figure into the final acoustic equation.

4.8 Summary of Acoustic Equation Terms

Individual terms of the acoustic equations used in fishery surveys are briefly explained in Section 4. Further explanation of some of these and their application is given in Section 6.

4.8.1 Source Level

SL = 10 log (intensity of source/reference intensity)

where the reference intensity is that of a wave of rms pressure 1μPa.

SL is given in dB/1μPa/1m.

4.8.2 Receiving Sensitivity

SRT is given in dB/1Volt/1μPa.

4.8.3 SL + SRT

This is a combination of the two parameters which is most conveniently obtained during calibration (see section 7). It avoids difficulties inherent in separate measurements of SL and SRT.

4.8.4 Transmission Loss

$TL = 20 \log R + \alpha R$

The one-way loss due to spreading and absorption. Not normally used in fisheries acoustics.

$2TL = 40 \log R + 2\alpha R$

Two-way loss for single targets.

$TL_2 = 20 \log R + 2\alpha R$

Two-way loss for schools or layers.

4.8.5 Target Strength

$$TS = 10 \log \frac{\text{reflected intensity 1 m from the target}}{\text{incident intensity which strikes the target}}$$

4.8.6 Volume Back-Scattering Coefficient

$$S_V = 10 \log \frac{\text{back-scattered intensity from unit volume at 1 m distance}}{\text{incident intensity}}$$

4.8.7 Reverberation Level

$$RL = 10 \log \frac{\text{reverberation power at the transducer terminals}}{\text{power generated by reference intensity}}$$

where the reference intensity is that of a plane wave of rms pressure 1μPa

4.8.8 Beam Factor

10 log Ψ dB

The equivalent beam of solid angle Ψ steradians derived by integration of the actual beam pattern.

4.8.9 Biomass Calculation

Biomass is defined as the density of fish (tonnes per square nautical mile) in the area surveyed, derived from the integrated echoes. The integrator output (Vo) is multiplied by a factor which includes

SL + SRT	dB
target strength of the species being surveyed	dB/kg
equivalent beam factor	dB
and other instrumentation factors such as	
transmitted pulse duration	dB
repetition rate of transmitted pulse	dB
system gain	dB
integrator constant	dB

These factors are considered in section 8.4.1.

5. ACOUSTIC PROPERTIES OF FISH

When an acoustic wave strikes a fish a proportion of the energy is reflected (the echo). For acoustic surveys we need to determine the amount.

Some discussions on the way that acoustic waves interact with fish-like objects and how fish as simple 'targets' fit into the acoustic equations took place in sections 2.8 and 4 respectively. Chapter 5 examines practical aspects of the characteristics of fish which affect the echoes so that the various factors involved can be assessed. These relate to fish size, morphology, physiology and orientation. The frequency of isonification has an effect on TS and is discussed in relation to fish size. Various methods of making TS measurements are described and published values of TS for some species are given. Work is continuing to improve the knowledge of fish TS and the factors which affect it.

5.1 Target Strength

Target strength (TS) is defined by equation 30 as 10 times the logarithm of the reflected intensity (I_R) at one metre from the fish, divided by the intensity which strikes the fish, i.e. the incident intensity (I_1). i.e. $10 \log I_R/I_1$.

The term target strength originates from Naval acoustics and the simplest object to consider as an acoustic 'target' is the sphere because it radiates its echo equally in all directions.

If an idealized perfectly reflecting sphere has a radius a, the amount of energy reflected depends on the acoustic cross-section σ of the sphere which is πa^2, i.e. the area of a circle of radius a. Acoustic cross-section is defined as, 'that plane area intercepting an amount of energy, which, if it were scattered equally in all directions would produce the observed echo'. In the case of the sphere the amount of energy intercepted will be $\pi a^2 I_1$. At a distance of 1 m from the sphere, the reflected intensity I_R will be equal to $\pi a^2 I_1$ divided by the area of a 1 m radius sphere, $4\pi \times 1$ so that

$$I_R = \pi a^2 I_1 / 4\pi \times 1$$

$$\therefore \quad I_R/I_1 = a^2/4$$

in decibel terms $TS = 10 \log a^2/4$(dB) ..... (38)

If the reference TS is taken to be 0dB then the target would have a radius of 2 metres, not a practical size.

The energy scattered by a target occupies 4π units of area at one metre from the target when the area corresponding to σ is in the target position. Sigma is the 'scattering' cross-section of the sphere which gives the same TS as the specified target under given conditions. These are that the area corresponding to σ is perpendicular to the incident plane waves of uniform intensity. For these conditions we can say that the scattered intensity is $\sigma/4\pi$. In decibels the back-scattering coefficient is the target strength.

If σ = scattering cross-section = πa^2

$$a^2 = \sigma/\pi$$

so substituting in equation 38

$$TS = 10 \log \sigma/4\pi \qquad \ldots\ldots\ldots\ldots\ldots (39)$$

Fish are neither spherical, nor rigid so they do not scatter uniformly, the nearest that many of them approach to a uniform shape is the cylinder and it is interesting to consider this shape as a simple model. The TS of a small acoustically rigid cylinder of length L metres is given by Urick (1975) as

$$10 \log aL^2/2\lambda \quad \ldots\ldots\ldots\ldots\ldots (40)$$

a is the radius and λ the wavelength, both in metres.

Equation 40 shows that the TS of a small cylinder is directly proportional to the square of the length and inversely to the wavelength. The ratio of length to acoustic wavelength L/λ is important because it determines the wave 'interference' effects along the surface of the cylinder and these affect the number of 'lobes' appearing in the response pattern see 2.8. The longer the cylinder or the smaller the wavelength, the greater is the interference effect, resulting in more maxima and minima of acoustic energy, hence a directional response with more spikes, or lobes. Equation 40 is correct if the cylinder remains perpendicular to the acoustic waves.

Fish are composed mainly of flesh and bones which have an acoustic resistance (impedance) quite similar to that of water, so the amount of reflected energy from these substances is small (Shibata, 1970). If we apply the TS formula for a cylinder of air, to fish, it is necessary to use a factor to correct for the difference in acoustic resistance of the materials. It is evident that the fish would have a TS lower than a cylinder of air of the same size. The factor (γ^2) to correct for a cylinder of fish flesh instead of air, is derived from the relative impedance (Z) of seawater and fish flesh.

$Z_F = \rho c(F)$ where ρ is the density of the fish flesh (kg/m^3)

c is the speed of acoustic waves through the fish flesh. m/s

$Z_W = \rho c(W)$ where ρ is the density of seawater (kg/m^3)

c is the speed of acoustic waves in sea water. (m/s)

The factor $\gamma^2 = [(Z_F - Z_W)/(Z_F + Z_W)]^2$ ..... (41)

TS of the cylinder of fish flesh becomes

$$10 \log (aL^2/2\lambda)\ \gamma^2 \text{ dB} \quad \ldots\ldots\ldots\ldots (42)$$

As an example, for Atlantic mackerel (Scomber scombrus)

$Z_F = 1.627 \times 10^6$ $Z_W = 1.54 \times 10^6$

giving a value of $\gamma^2 = 7.63 \times 10^{-4}$

Assuming the effective fish length L is 0.4 m

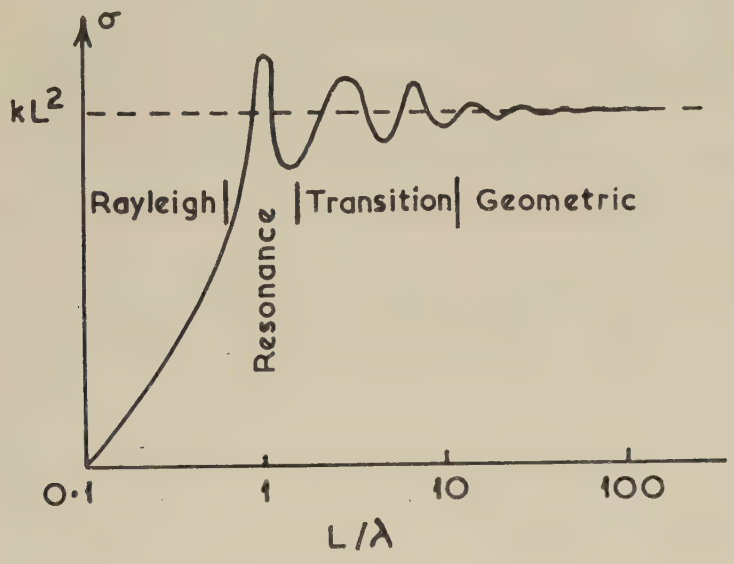
" " " " radius a is 0.025 m

" wavelength λ is 0.039 m (f = 38 kHz)

$$TS = 10 \log \frac{0.025 \times 0.4^2}{2 \times 0.039} \times 7.63 \times 10^{-4} = -44 \text{ dB}$$

Generally the polar diagrams from fish are different to those from cylinders because the energy is more widely distributed from fish. This is attributed to the internal structures and impedances and their relative distribution within the body, e.g. the swim-bladder in relation to the backbone and the curvature of the body's outer surface.

Figure 36



Acoustic scattering from a fish is considered to fall into one of the following regions see Figure 36 from Lytle and Maxwell (1982). At any particular frequency not all parts of the fish may be in the same region.

1. Rayleigh scattering when the fish is small compared to λ, i.e. $L \ll \lambda$. In this case $\sigma \propto$ to $(\text{Volume})^2$ and λ^{-4}. Transition between this and the intermediate region occurs when the dorsiventral dimension of the fish is close to λ, (a maximum dorsiventral size is 0.2 of total length).
2. Resonant region where the swimbladder is caused to vibrate in sympathy with the frequency of the acoustic wave. It consequently absorbs and re-radiates more power than predicted by the Rayleigh approximation. In principle this effect can be used for sizing fish but in relation to present-day acoustic surveys the source of error in estimation due to resonance of small organisms is most important, see 9.6.4.
3. Transition or intermediate region where $\sigma \propto L^2$ and is largely independent of λ. The dorsiventral dimension is similar to λ, this applies to some of the smaller fish e.g. at 38 kHz λ = 39 mm.
4. Geometric, where the fish length $L \gg \lambda$. Half of the scattered power is reflected in various directions from curved surfaces of the dominant scattering parts. The other half is confined to a narrow angular region in the forward direction of the incident wave thus interfering with it below the fish.

Although in marine fish the volume of the swimbladder is only 5% of total fish volume (7% in freshwater fish) the fact that it is gasfilled, with a markedly different impedance to fish flesh, makes it a very significant acoustic reflector. The evidence seems to show (Foote, 1980) that often about 90% of the echo from a fish is due to the swimbladder alone, i.e. the TS of fish without a swimbladder is 10-15 dB lower than those of similar size with a swimbladder.

Gas filled swimbladders are used by fish to adjust their buoyancy when migrating up or down in the water column. They can tolerate sudden pressure increases of up to 400%, but decreases of only 50%, thus they can dive more easily than ascend. The state of the swimbladder at any given time depends on the extent of the last significant vertical movement and the rate at which it took place. This indicates that the swimbladder may cause changes of TS with time, but for example with the cod it has been shown that the maximum overall change is likely to be about 1 dB (Harden Jones and Scholes, 1979).

Midttun and Hoff (1962) measured the TS of a dead saithe with an intact swimbladder and found that the polar plot of TS around the dorsal aspect could be closely approximated by calculation using equation 40. An X-ray showed the angle of the near cylindrical swimbladder to the vertebral column of the fish. Many fish have swimbladders closer in shape to a prolate spheroid.

To sum up, the size of echo from a fish depends on the exact interaction of the fish with the acoustic waves striking it. The important factors are:

1. Dimensions shape and angle of the swimbladder
2. " " " " " " body
3. Acoustic impedance of 1 and 2
4. " wavelength.

5.2 Measurement of Fish Target Strength

In order to convert data collected on acoustic survey into population estimates it is essential to have precise estimates of fish target strength. The methods used to obtain these are by having single fish, or numbers of live fish in a cage, stunned individuals; or by measuring signals from wild fish in situ. In all cases the mean dorsal aspect TS is required.

5.2.1 Direct TS measurements

These have been performed on caged or tethered fish of various species in order to gain understanding of the effects on TS of variables such as the acoustic wavelength, size of fish, orientation and state of swimbladder. To make suitable observations requires carefully controlled conditions; but even so, there is great difficulty in knowing the physiological state of the fish and determining if their behaviour is 'normal'. Experiments on individual free-swimming fish in a cage at 10 m range were carried out by Goddard and Welsby (1975). The mean amplitude of the echoes from 1000 transmissions on each fish were converted into TS by reference to the system calibration. Four species were investigated, cod, haddock, saithe and dogfish. TS equations were produced from these data but echo-integration is the most commonly used technique for abundance surveys so it is the mean scattering cross section per fish, or mean echo intensity that is needed. A further analysis by Forbes (1975) used mean squared echo amplitude to convert results to mean echo intensity and some of the results are given below.

Table 3. Mean of individual target strengths

	Mean length	Frequency (kHz)			
		10	30	100	
Cod	0.491 m	-39	-32.1	-33.9	dB
Haddock	0.364 m	-41.5	-38.9	-38.3	dB
Saithe	0.401 m	-41.2	-39.6	-35.6	dB

Table 4. Mean scattering cross section expressed as target strength

Cod	-35.5	-28.9	-31.9	dB
Haddock	-38.8	-35.7	-36.09	dB
Saithe	-40.3	-38.4	-34.8	dB

Table 5. Mean scattering cross section per kg expressed as TS

	TS/kg re mean fish length				
Cod	-33.3 dB	-36.5	-29.9	-32.8	dB
Haddock	-33.7 dB	-35.7	-32.5	-32.9	dB
Saithe	-36.5 dB	-40	-37.2	-33.5	dB

Another feature of the work by Goddard and Welsby was the measurements made with number of fish in the cage which showed that the TS increased by slightly more than the 3 dB expected per doubling of numbers.

Recently work has concentrated on integrating echoes from a number of fish, e.g. Dunn (1979), Edwards (1979). Fish were weighed so that the total biomass in the cage was known. After the fish had settled (sometimes this took more than 24 h) and steady mean values were obtained from the integrator, a mean TS for unit mass of a known size range for the particular species was derived. Calibration of the system in terms of integrated output per unit volume back-scattering coefficient (Sv) was achieved by substituting a standard target for the fish.

Methods of measuring TS on survey were examined by Ehrenberg (1972), most of them had drawbacks and he proposed the use of a new method, the dual beam, described in detail (Ehrenberg, 1974).

The dual beam measures the target strength of individual fish in-situ if the density is low enough, (a requirement for all in-situ measurements) whilst also recording the total back-scattered intensity.

As the name implies, the transducer forms a dual beam which comprises coaxial narrow and wide beams, the main lobe of the narrow beam covering approximately the same volume as the region of unity response in the centre of the wide beam. The ratio of received intensity for targets in the two beams is given by

$$I_n/Iw = k_n/kw \left[b_n(\Theta, \phi) \right]$$

where I_n = intensity in the narrow beam

k_n = constant for the narrow beam

Iw = intensity in the wide beam

kw = constant for the wide beam

$b_n(\Theta\phi)$ = directivity function for the narrow beam, defined as the distribution of acoustic power transmitted in different direction (Θ,ϕ) relative to the acoustic axis of the transducer;

b is a quantity between 0 and 1.

Transmission occurs only on the narrow beam, but reception is on both wide and narrow. Signals are processed via amplifiers with 40 logR + 2αR characteristics for fish target strength analysis and 20 logR + 2αR for total biomass estimation. The narrow beam is 6° and the wide is 25°.

The scattering cross-section σ of a fish at position (Θ,ϕ) in the beam is $\sigma = I_n/k_n\left[b^2(\Theta\phi)\right]$. From this the fish's mean scattering cross-section and its variance may be estimated. σ is the effective-area of a fish which is normal to the incident acoustic energy when the fish has the properties of a spherical reflection pattern and total reflection.

Providing that fish densities are sufficiently low for the selection of individual echoes and at any time comprise one species only, target strength data may be collected and used during the progress of a survey. The intensity of back-scattered acoustic energy from fish concentrations received on either beam is proportional to fish density.

By using the mean target strength extracted from the dual beam system, estimates of biomass can be obtained. There is no complex mathematical analysis involved in this process but a computer is necessary to perform the signal processing in real time. Fishing is necessary to identify the species and obtain length distributions (Traynor, 1975).

5.2.2 Indirect TS measurements

Craig and Forbes (1969) proposed a method of measuring fish target strength by removing the effects of the transducer beam pattern which was later considered by Ehrenberg (1971) and Traynor (1975). It statistically corrects an echo strength distribution to a TS distribution using beam pattern directivity measurements. The assumption is made that fish are distributed uniformly within the sampled volume, but in practice this is not always so. For small sample sizes the technique breaks down.

Another method which also uses a single beam transducer has been successfully exploited by Robinson (1979). In this the difficulty due to the unknown position of a fish in the beam is overcome by accepting the premise that, whilst the location of a particular fish in an acoustic beam cannot be known, or calculated, if a sufficient number of fish are taken into account, the probability that all positions will be occupied at some time can be described statistically. In order to use such a method the following conditions must be satisfied.

1. the directivity pattern of the transducer must be known.
2. a valid assumption of the likely distribution of fish in the beam is necessary.

A beam pattern density distribution results from these two factors, which when convoluted with the fish target strength distribution, results in an intensity distribution of received echoes. The fish target strength distribution has to be recovered from the other two distributions, of which the beam pattern density has already been discussed. In order to obtain a suitable distribution of received echo intensity it is necessary to collect sufficient echoes which are without doubt from single fish. To satisfy the statistical requirement about 10^4 echoes are needed although this depends on the distribution so a number of practical problems must be overcome.

3. the density of fish must be low in relation to the dimensions of the beam and the pulse length in order to provide a satisfactory number of single echoes.
4. echoes from single fish must be extracted without ambiguity.
5. there must be a positive means of species identification and size measurement, i.e. a good sample of the fish from which echoes are recorded must be captured.
6. the schools sampled should be predominantly of one species.

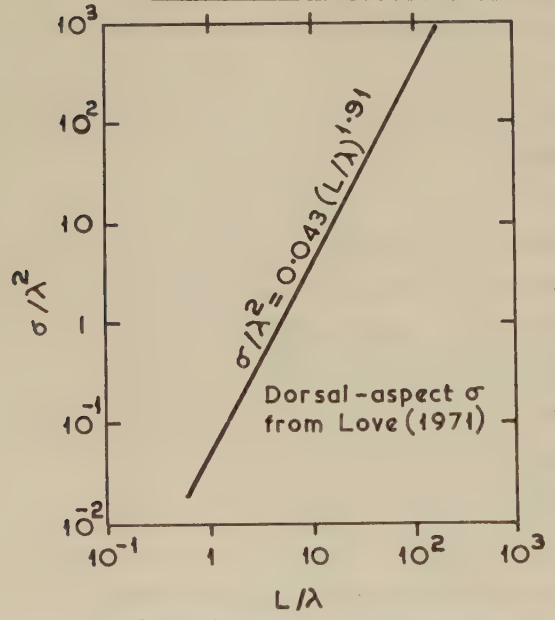
For 3 above to be satisfied, it is often necessary to work on the edge of a school, or to wait until it partially disperses. Even then a towed transducer may need to be lowered to with 20-30 m range of the fish. Then the beam is relatively narrow at the depth of the fish, giving a greater probability of receiving one fish echo per pulse volume.

To meet (4) the echo amplitudes must be accurately recorded from the calibrated echo-sounder with 40 logR + 2αR time-varied gain. Magnetic tape is suitable for the recording. After extraction from the tape the signals are digitised before going to an electronic processor which selects those from single fish on the following basis.

7. they do not exceed a certain time duration at the origin.
8. they do not exceed a given amplitude.
9. they are clearly separated by a specified amount from adjacent signals.

This method of in-situ measurement appears to be capable of achieving an accuracy of ± 0.5dB if the distribution is unimodal and the standard deviation less than 2.5 dB. It needs a computer for the analysis. Although it is desirable to obtain a continuously updated record of target strength during survey, in practise a period sufficient to secure the 10^4 or so echoes is dedicated to the purpose when conditions are suitable, 30 minutes is often adequate. The ship drifts for this purpose. Indirect measurement of TS are described by Ehrenberg et al. (1981) and by Clay (1983).

5.3 Fish Size and Target Strength Dependence



It is clear from the previous parts of Chapter 5 that fish target strength is complex and far from being fully understood. There is a relationship between size of fish and TS but it varies widely with species. Certain classes appear to have similar TS/length characteristics within limits, e.g. gadoids, although there is limited agreement as to the TS to be used for particular species within this group. Love (1971), Figure 37, shows the results of dorsal-aspect measurements by nine workers including his own which covered many species and a wide range of frequencies. He gives a regression line equation of

$$TS = 19.1 \log L + 0.9 \log\lambda - 23.9 \quad \ldots\ldots\ldots\ldots (43)$$

where L and λ are in metres

which may be compared with

$$TS = 24.5 \log L - 4.5 \log\lambda - 26.4 \quad \ldots\ldots\ldots\ldots\ldots\ldots (44)$$

of McCartney and Stubbs (1971) from their own measurements on live fish. The technique of data reduction due to Love (1971) also used by Goddard and Welsby, was target strength expressed as an area and normalised by the square of the wavelength, is regressed on the fish length normalised by the wavelength.

Equations for three species were given by Forbes (1975) from the Goddard and Welsby data

$$\text{Cod} = 23.5 \log L - 3.5 \log\lambda - 29.4 \text{ dB} \quad \ldots\ldots\ldots\ldots\ldots\ldots (45)$$

$$\text{Haddock} = 22.7 \log L - 2.7 \log\lambda - 30.4 \text{ dB} \quad \ldots\ldots\ldots\ldots\ldots\ldots (46)$$

$$\text{Saithe} = 25.6 \log L - 5.6 \log\lambda - 35.0 \text{ dB} \quad \ldots\ldots\ldots\ldots\ldots\ldots (47)$$

showing surprising differences between cod and haddock, fish reasonably similar in morphology and physiology.

At 38 kHz Nakken and Olsen (1977) obtained a relationship of TS against length for cod of

$$24.6 \log L - 60.8 \quad \ldots\ldots\ldots\ldots\ldots\ldots (48)$$

and for sprat at the same frequency

$$17.2 \log L - 66.6 \quad \ldots\ldots\ldots\ldots\ldots\ldots (49)$$

5.4 Fish Tilt Angle

Fish need to conserve energy as do other creatures so there is no reason to suppose that they are constantly executing sudden manoeuvres. Nevertheless, there is evidence to show that in certain circumstances their behaviour results in low TS, e.g. diving when under the passage of a ship as described in 9.5.

The directional patterns shown in Figure 38 are theoretically ideal but illustrate in principle the type of pattern possible for a given length of fish insonified by a frequency (f). Three frequencies are taken as the basis for these diagrams from which it is evident that the lower the frequency the broader the response pattern, hence there is less dependence on tilt.

Figure 38

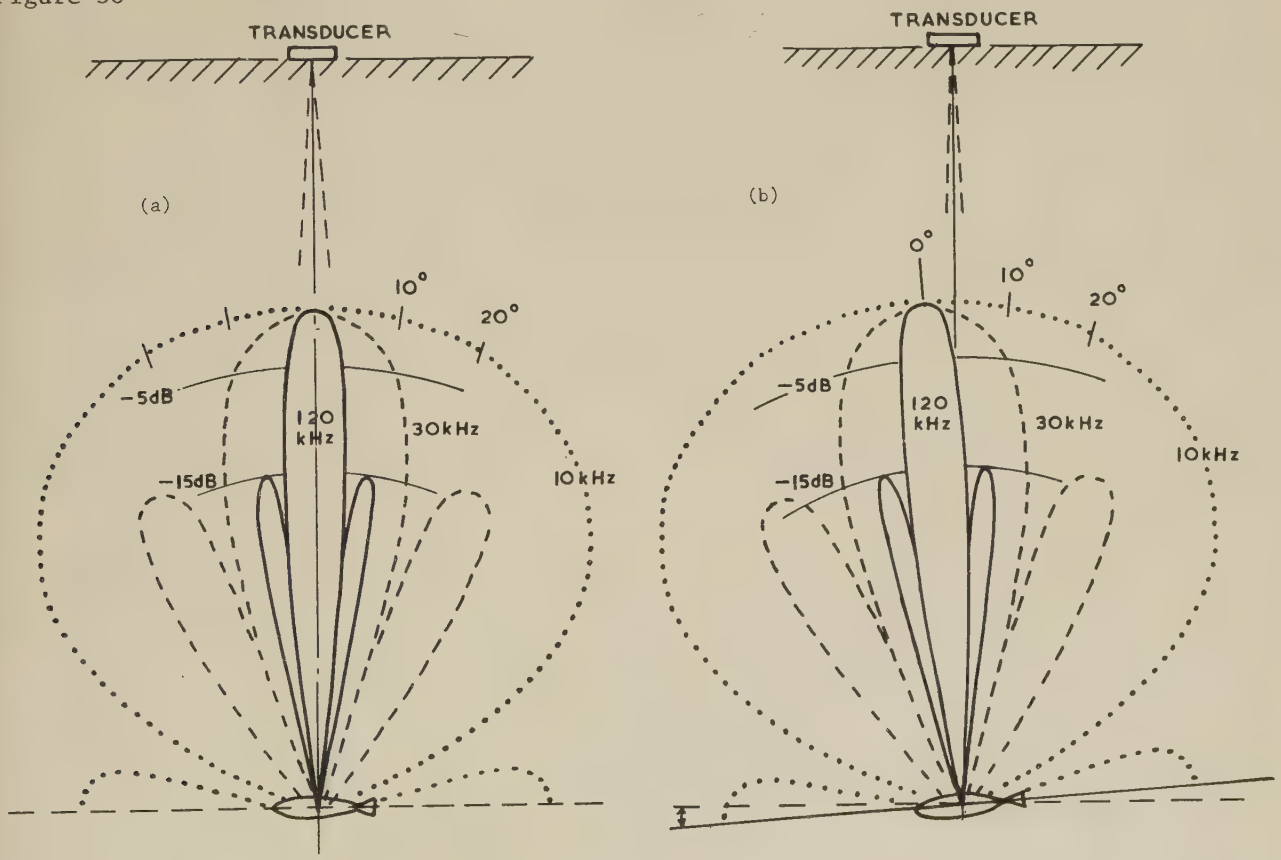


Figure 38(a) shows the maximum response of the fish in the direction of the transducer but in practice this is not always perpendicular to the long axis of the fish. In Figure 38(b) a few degrees of tilt are very significant when f = 120 kHz. The larger the fish for a given wavelength, the narrower will be the lobes in its directional pattern,

hence the greater will be the rate of change as the fish tilts up or down from its normal swimming state.

5.5 Acoustic Frequency and Fish Target Strength

There is little evidence to show a significant change of TS with frequency. If we use equation (44) which is valid for fish in the length range $0.8<L/\lambda<20$, the TS at 120 kHz would be about 2 dB greater than at 38 kHz and similar results would be obtained for (45) (46) and (47). Evidence from field observations that this is so and has practical significance is given by Saetersdal et al. (1982). Results from 38 kHz and 120 kHz calibrated systems were compared when surveying the same biomass concentrations and these indicate that for fish of the length studied (100-250 mm) the volume back scattering strength, hence by inference the TS of the individual fish is frequency dependent. It appears that the fish TS may be approximately 4 dB higher at 120 kHz than at 38 kHz. This difference has proved to be useful in helping to discriminate between fish and plankton for the 120 kHz system gave consistently higher readings of mean volume back scattering strength from fish whilst the 38 kHz system gave higher values for plankton.

5.6 Fish School Target Strength

Acoustic surveys of fish are mostly based on the assumption that total echo intensity from schools is equal to the arithmetic sum of echo contributions from individual fish, which is justified if the echoes are uncorrelated. In a uniform population therefore, doubling the number of fish should double the echo power, i.e. produce an increase of 3 dB in target strength. There was some evidence in work by Goddard and Welsby (1975) that a small but significantly greater increase than 3 dB actually occurred. Smith and Welsby (1979) examined this noting that the result for 32 fish was about 1.5 dB higher than predicted, an excess of about 40% in echo intensity from this group of fish.

Such an apparent increase in TS cannot be explained by coherence of the echoes from adjacent fish because for this to be significant the mean spacing of the fish must be similar to λ. For the size of fish (300 mm) and λ of 15 mm used in the experiment this clearly was not so.

Multiple scatter theory was examined to see if the excess could be accounted for in this way. It is said that multiple scattering takes place when the incident intensity intercepted by one target is re-radiated in all directions and a portion is in turn intercepted by a second target, this portion also being re-radiated in all directions, some towards the transducer. If the second target had not been in position this fraction of the energy would not have reached the transducer. There is also the possibility that the re-radiation from the second target is further re-radiated from the first target and so on. Investigation has shown that generally the effects of multiple scattering are too small to be significant, although this is not certain for all situations.

Experimental data obtained from a large herring school have been analysed and compared to a theoretical multiple scatter model which is shown to adequately describe the school echo characteristics, Ertugrul and Smith (1982). They conclude that

fish abundance measurements which employ echo-integration techniques could substantially underestimate the fish numbers. The smaller the school and the lower the density of fish the less likely it is that underestimation will occur.

Another effect in fish schools is the acoustic shadowing of fish low down in a school by those above them. Examination of this and other effects due to the schooling of fish is beyond the scope of this manual but readers are referred to Lytle and Maxwell (1982) and the Foote (1983).

6. CONCEPTS OF ACOUSTIC ESTIMATES OF AQUATIC BIOMASS

A newcomer to this work, embarking on his first survey cruise aimed at providing an estimate of a given fish stock, may perceive the exercise lying ahead of him as routine. The survey vessel, carrying sophisticated equipment, will sail to a given area, measure a unit fish stock, and then compute the result - mission accomplished! Such a conception is understandable because quantitative acoustic methods are known to represent a powerful tool in present-day fisheries management. But the procedures are more complicated than is generally realised and there are many implications with respect to precision and errors in the estimates.

This section deals with some general concepts and processes related to a biomass estimate by acoustics. Clarification of what comprises an acoustic estimate may be useful at this stage and will facilitate understanding of subsequent discussions. To avoid ambiguity later an assumption is made here that, when referring to a fish stock, we mean a population comprising a single species with a narrow but normal length distribution.

6.1 Measurement of Volume Back-Scattering Strength

In section 4.5 we considered fish schools as targets in a simple manner. The purpose of Chapter 6 is to examine the theory and to show how the principles of measuring backscattering strength and reverberation level, are put into practise for the quantitative measurement of schools.

A number of simplifying assumptions regarding the distribution and density of fish (scatterers) plus other factors were given in section 4.5 and it is necessary for these assumptions to be fulfilled if accurate results are to be obtained. In practise the actual beam pattern of the transducer is replaced by the equivalent beam Ψ, (section 4.6). The concept that there is unity response inside this beam and zero response outside is now adopted to simplify the explanation of volume backscattering.

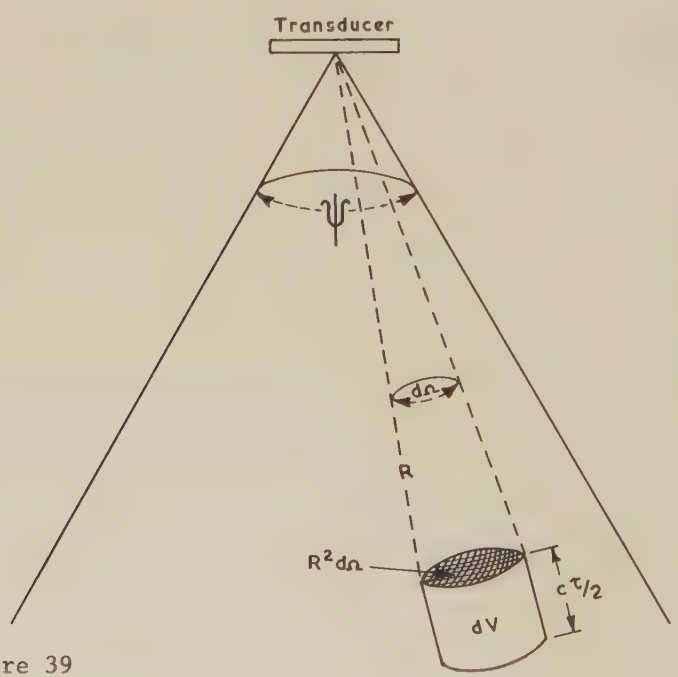


Figure 39

In Figure 39 the volume dV has an end face surface area of $R^2 d\Omega$, where R is the range from the transducer and $d\Omega$ is the solid angle in steradians subtended by dV at the transducer. The length of dV is sufficiently small that, when insonified by a pulse, all scattering produced from its volume is received by the transducer at the same instant of time. This can

be visualised by first considering the front surface of the pulse reaching and acting upon the scatterers at the rear of dV. The energy backscattered from this rear area will arrive at the transducer with the energy backscattered from the front area of dV by the rear surface of the pulse. Thus the length of dV is shown to be $c\tau/2$ (a similar principle is illustrated when the minimum separation of two targets in range by $c\tau/2$ is necessary to ensure that they are resolved, one from the other, see Figure 18.

The volume dV is therefore

$$dV = R^2 \, c\tau d\Omega \qquad \ldots\ldots\ldots\ldots\ldots\ldots (50)$$

We need to determine the intensity of the acoustic backscattering from this volume and to do this must introduce a term which has some similarity to target strength. This is the volume backscattering coefficient s_v. It is defined as the ratio, of backscattered intensity (Ib) produced by unit volume at 1 m from the volume, to the intensity of the incident wave I_1, i.e.

$$s_v = Ib/I_1 \quad \text{and} \quad S_v = 10 \log s_v \qquad \ldots\ldots\ldots\ldots\ldots\ldots (51)$$

Thus the intensity from dV is

$$s_v . R^2 . \, c\tau . d\Omega$$

to include the whole beam we substitute Ψ for $d\Omega$

$$s_v . R^2 . \, c\tau . \Psi$$

It is now possible to determine the reverberation level (RL) at the transducer arising from this expression. If the intensity from the transducer is I, it will be reduced in proportion to R^4 i.e. (40 logR) by the journey to and from the volume dV.

$$RL = IR^{-4} s_v . R^2 \, c\tau\Psi .$$

which in logarithmic terms is $RL = SL - 20 \log R + 10 \log s_v + 10 \log c\tau + 10 \log\Psi$

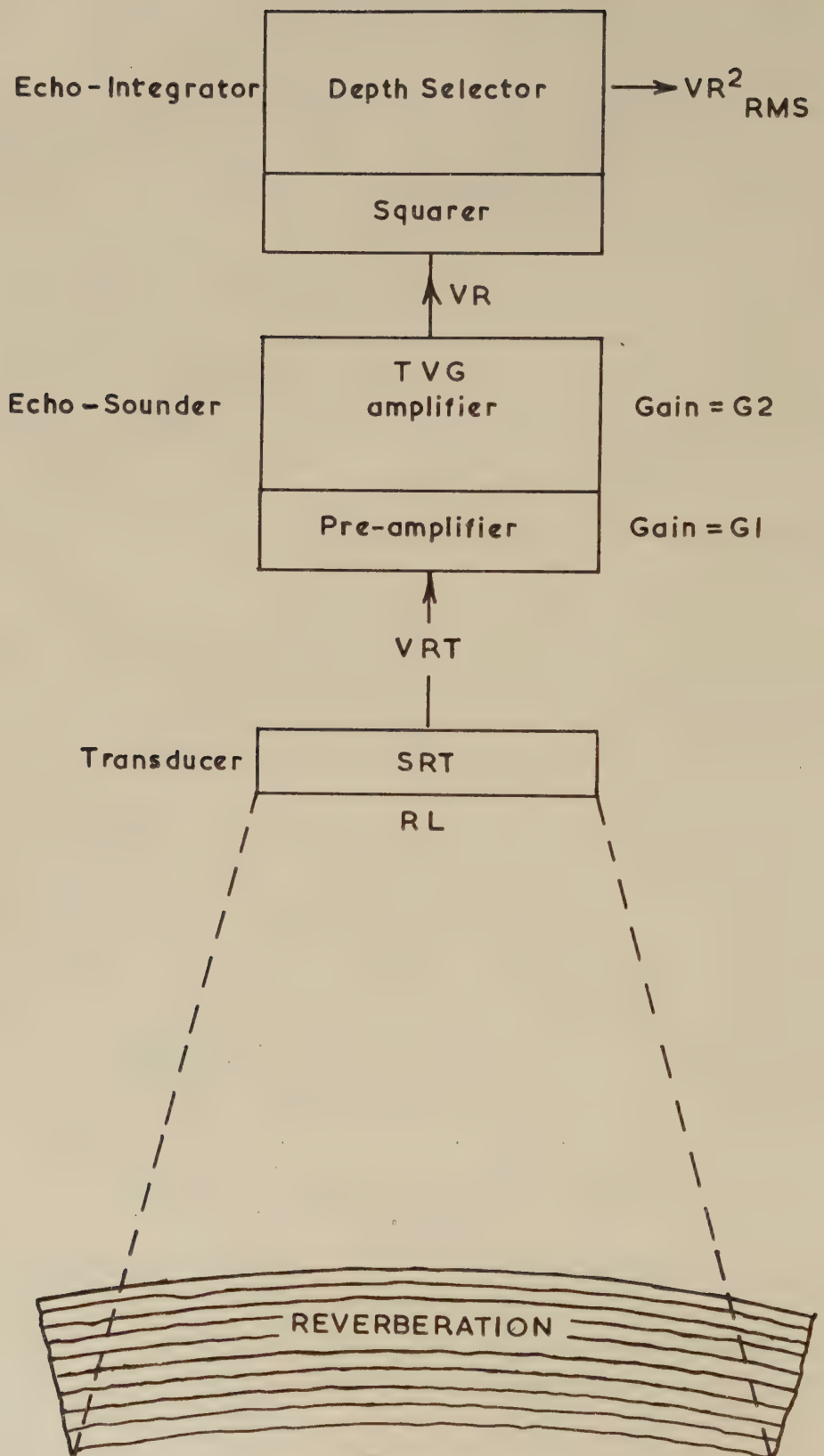
Note that we are left with 20 logR the same result as in section 4.5. Ψ can be calculated from either eqn. 34 or 35. Under practical conditions the absorption loss $2\alpha R$ must also be taken into account so we would have $-(20 \log R + 2\alpha R)$, but when an exactly correct TVG is used this term is fully compensated and does not appear in the equation.

In Figure 40 the pressure waves which make up RL act on the transducer to produce a voltage VRT whose amplitude at any instant of time is equal to RL + SRT (SRT is the transducer sensitivity as a receiver expressed in dB/1V/1μPa). So we can now say

$$VRT = SL + SRT + S_v + 10 \log c\tau/2 + 10 \log\Psi \qquad \ldots\ldots\ldots\ldots\ldots (52)$$

This is convenient because SL + SRT is a lumped parameter which can be measured by means of the standard target calibration procedure (see Chapter 7). It can be seen from Figure 40 that the voltage VRT is processed through the echo-sounder first by a fixed gain amplifier G1 and then in the TVG amplifier G2. These gains (in dB) must be taken into account, i.e. included in the eqn. G2 is normally the gain figure at maximum range of the TVG. All voltages from the echo-sounder are squared in the echo-integrator to convert from pressure to intensity proportionality. Adjustment for speed of vessel, selection of depth and depth interval is made.

Figure 40


Echo-Integrator
Depth Selector
VR^2 RMS
Squarer
VR
Echo-Sounder
TVG amplifier
Gain = G2
Pre-amplifier
Gain = G1
VRT
Transducer
SRT
RL
REVERBERATION

6.2 Mean Volume Back-Scattering Strength (MVBS)

So far we have only related the S_v to an instantaneous value theoretically produced by one pulse volume. A more meaningful measurement parameter is the MVBS, which is S_v averaged over one or more transmissions and over a certain range interval ΔR as well as unit distance.

For an integration or depth interval $\Delta R = R_2 - R_1$, the volume backscattering strength for one transmission is a measure of the instantaneous acoustic intensities reflected from each m^3 of water added and averaged over ΔR. Along the distance sailed, (e.g. one nautical mile) where there are a large number of successive transmissions, the resulting mean volume backscattering strength (MVBS) would be the MVBS per transmission, averaged over ΔR, and also the relevant unit distance. In logarithmic terms the MVBS denoted by $\bar{S}_v$ can be expressed by

$$\bar{S}_v = 10 \log \bar{\rho}_v + \overline{TS} \quad dB \qquad \ldots\ldots\ldots\ldots (53)$$

where $\overline{TS}$ = the mean TS of individual fish in the total insonified volume

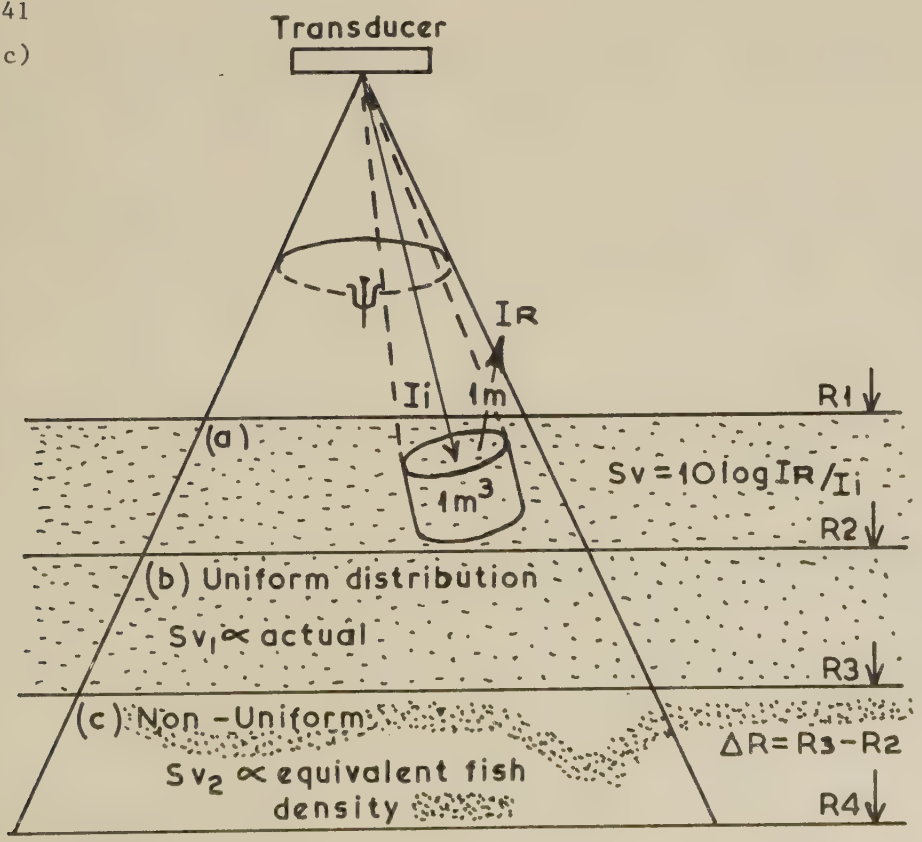
ρ_v is the mean density (fish/m^3)

If $\bar{S}_v$ is known, the mean density of fish targets for an integration interval can be estimated provided that $\overline{TS}$ is also known. Two important factors are evident from the above.

(a) the MVBS is a biomass scattering parameter, independent of system parameters

(b) when $\bar{S}_v$ is averaged over a selected integration interval rather than the actual cross-section of a fish layer, the MVBS will relate to the equivalent fish density (assuming the fish to be uniformly distributed throughout the whole volume of the depth interval), but not the actual density, illustrated in Figure 41b-c.

Figure 41
(a)(b)(c)



Although the MVBS provides a measure of relative biomass density ($\overline{TS}$ not known), like the observed M-values discussed under 6.3, there is an important difference because the MVBS has a universal meaning, but the M-values represent arbitrary quantities. Thus, the MVBS obtained from one vessel/system in a given area is directly comparable with MVBS values collected by another vessel/system in a different area. Similar comparisons between M-values of two different survey vessels are not meaningful, because they depend on the scattering parameter and also on the selected control settings.

Expressing the above more formally we can say that the mean volume backscatter from a single acoustic transmission passing through a range interval $\Delta R = R_2 - R_1$, is the sum of the individual pulse volume scattering coefficients divided by the range interval hence

$$\overline{\overline{s_v}} = \frac{1}{C_i (R_2 - R_1)} \sum_{n=1}^{n=N} (V_o^2)_n \qquad \ldots\ldots\ldots\ldots (54)$$

where C_i represents the instrument parameters of SL, SRT, Ψ etc

$N = \Delta R/(c\tau/2)$ is the number of pulse-lengths occurring in ΔR,

$(V_o^2)_n$ = squared output voltage at the n^{th} one of these.

During actual echo surveys, the selected measurement unit could be the MVBS averaged for all acoustic transmissions occurring over a distance of one nautical mile. In this case we have

$$\overline{\overline{MVBS}}_{1\text{-mile}} = \bar{\bar{s}}_{vv} = \sum_{t=1}^{t=Tx} (s_v)/Tx \qquad \ldots\ldots\ldots\ldots (55)$$

where Tx is the total number of transmissions over one nautical mile, and $\bar{\bar{s}}_{vv}$ is now the doubly averaged pulse volume backscatter.

In summary: The mean volume backscattering strength (MVBS) measured over a given range interval and per unit distance is the product of an instrument constant and the average squared output voltage $(\overline{V_o^2})$ of a system using a 20 logR + 2αR TVG function. The MVBS is exclusively a biomass target parameter which can be compared between different survey ships and geographic areas, and as such, has a universal meaning.

6.3 Measurement of relative density

When a scientific echo-sounder works in conjunction with an echo-integrator acoustically surveying a fish stock, the output is proportional to the observed fish density (Midttun and Nakken, 1977), i.e.

$$\rho = C \times M$$

where ρ = fish density (tonnes/mile^2)

C = system calibration constant (tonnes/mile^2) per mm, ref. a 1 mile sample with standard control settings

M = observed integrator value (mm)

Imagine a survey vessel with this equipment (without it being calibrated) proceeding along a given survey track in a densely populated area. For each one-mile section sailed, the integrator is automatically re-set and the corresponding readings noted. After some distance there will be a set of values for integrated echo-intensities returned from the layer of the fish population. The observed values M_1, M_2, M_3, etc. represent

(a) a directly measured one-mile echo-abundance index for the insonified (sampled) water volume

(b) a relative area density (biomass/mile^2) between the individual one-mile sections.

It is important to note that the echo-abundance index is not only a function of fish density, but also of the thickness of the actual fish layer occurring within the integrated depth limits. Thus, if a scattering layer of 20 m thickness produces a reading M_{20} = 100 mm, a layer of equal density but only 10 m thickness would give half the reading, i.e. M_{10} = 50 mm. To summarise, the use of the integrator as a measuring device results in

(a) a measure of an echo-abundance within a given distance unit

(b) the measurement of relative area density between distance units.

6.4 Measurement of Absolute Density

From the simplified relationship for fish density ($\rho_v = C \times M$) the conversion of relative density values in millimetres into 'absolute' fish density (e.g. tonnes per square nautical mile of sea surface area) is achieved through multiplication with the constant 'C'. This 'integrator conversion constant', or scaling factor, is the key to the transformation of relative to absolute fish densities. It can be determined through different methods of calibration as explained in Chapter 7. Often though, the constant has been estimated from experimental data obtained from direct live fish calibration which has particular application to species that either have unknown target strength or simply do not lend themselves individually to acoustic measurements in the field. However, with digital integrators, and an advance in calibration with standard targets (Foote, Knudsen and Vestnes, 1982), coupled with improved knowledge of fish target strength, it has become increasingly attractive to estimate absolute densities through MVBS measurements. This approach can be explained by expanding the mathematical derivations given previously.

$$\overline{s_v}\,\Delta R = \frac{1}{C_i}\int_{R_1}^{R_2} V_o^2\, dR \qquad \ldots\ldots\ldots (56)$$

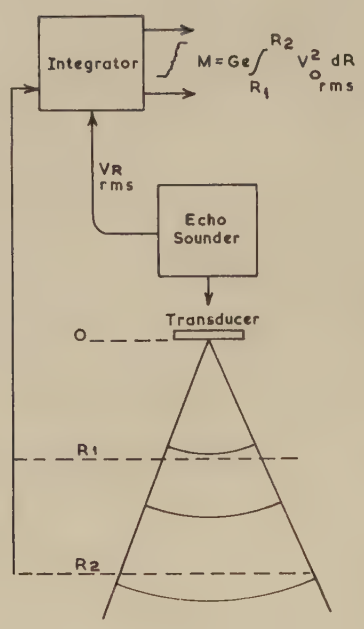
an echo-integrator is a device specifically designed so that its output (M) is

$$M = G_e \int_{R_1}^{R_2} V_o^2\, dR \qquad \ldots\ldots\ldots (57)$$

where G_e is the echo-integrator gain factor, V_o is the output voltage derived from VR,

fed directly to the input terminals of the integrator (Figure 42). Combining eqn 56 and 57 we obtain

Figure 42



$$\bar{s}_v \Delta R = M/C_i G_e \quad \ldots\ldots\ldots (58)$$

Now, by substituting for s_v and rearranging eqn 58 we may write

$$\rho_v \Delta R = M/C_i G_e \, (\sigma/4\pi) \quad \ldots\ldots\ldots (59)$$

The left hand side of eqn 59 is interpreted as an area density (ρ_A), i.e. $\rho_v = \rho_A \Delta R$, commonly expressed in tonnes/mile^2. For analog integrators where only one channel is available for integration over the whole depth column of interest, the area density is the most practical unit to work with. Hence, in logarithmic terms the expression for ρ_A becomes

$$10 \log \bar{\rho}_A = 10 \log M - 10 \log G_e - 10 \log C_i - \overline{TS} \quad \ldots\ldots\ldots (60)$$

which, as a working formula, is often written in the antilog form

$$\bar{\rho}_A = 10^{0.1(10 \log M - 10 \log G_e - 10 \log C_i - \overline{TS})} \quad \ldots\ldots\ldots (61)$$

demonstrating that, when the relevant instrument constants and the target strength of fish are known, the observed integrator readings (M) can be readily converted into absolute fish densities. In the case of digital echo-integrators the situation and hence the procedures are different. Built-in computing facilities allow for multi-channel integration with automatic print-out of $\bar{S}_v$ values in each depth interval over the pre-programmed distance unit. Because the computer memorizes and includes the constants G_e and C_i (60) in its computation of the MVBS values, the derivation of the equivalent fish density is now based on the relationship

$$10 \log \bar{\rho}_v = \bar{S}_v - \overline{TS} - 10 \log \Delta R \quad \ldots\ldots\ldots (62)$$

where, ΔR = the width of the integrator depth interval (m)

$\bar{\rho}_v$ = equivalent mean fish density within a depth interval (fish/m^3)

$\overline{TS}$ = mean target strength of the fish

Written in the antilog form, eqn (62) is

$$\bar{\rho}_v = 10^{0.1(\bar{S}_v - \overline{TS} - 10 \log \Delta R)} \quad \ldots\ldots\ldots (63)$$

which, when compared with eqn 61, shows the principal difference between the analog and digital-integrator output expressions.

In practical operations, it may be desirable to determine the MVBS for the whole integrated depth column, in addition to the values of individual depth intervals. Using first linear dimensions, this is achieved by summation of products as follows

$$\bar{s}_{vt}\,\Delta R_t = \bar{s}_{v1}\,\Delta R_1 + \bar{s}_{v2}\,\Delta R_2 + \ldots\ldots \bar{s}_{vn}\,\Delta R_n \qquad \ldots\ldots\ldots (64)$$

where, $\bar{s}_{vt}$ = the MVBS for all channels

ΔR_t = the total width of all integrator channels

$\bar{s}_{vn}$ = the MVBS in the n^{th} channel

ΔR_n = the width of n^{th} depth channel

By rearranging eqn 64 into a more general form, we have

$$\bar{s}_{vt} = \sum_{n=1}^{n=N} \frac{\Delta R_n}{\Delta R_t} \cdot \bar{s}_{vn} \qquad \ldots\ldots\ldots (65)$$

where N = number of channels available. By converting into logarithmic form, and bearing in mind that $10 \log \bar{s}_v = \bar{S}_v$, we obtain

$$\bar{S}_{vt} = 10 \log \sum_{n=1}^{n=N} \frac{\Delta R_n}{\Delta R_t} \cdot 10^{0.1(\bar{S}_v)_n} \qquad \ldots\ldots\ldots (66)$$

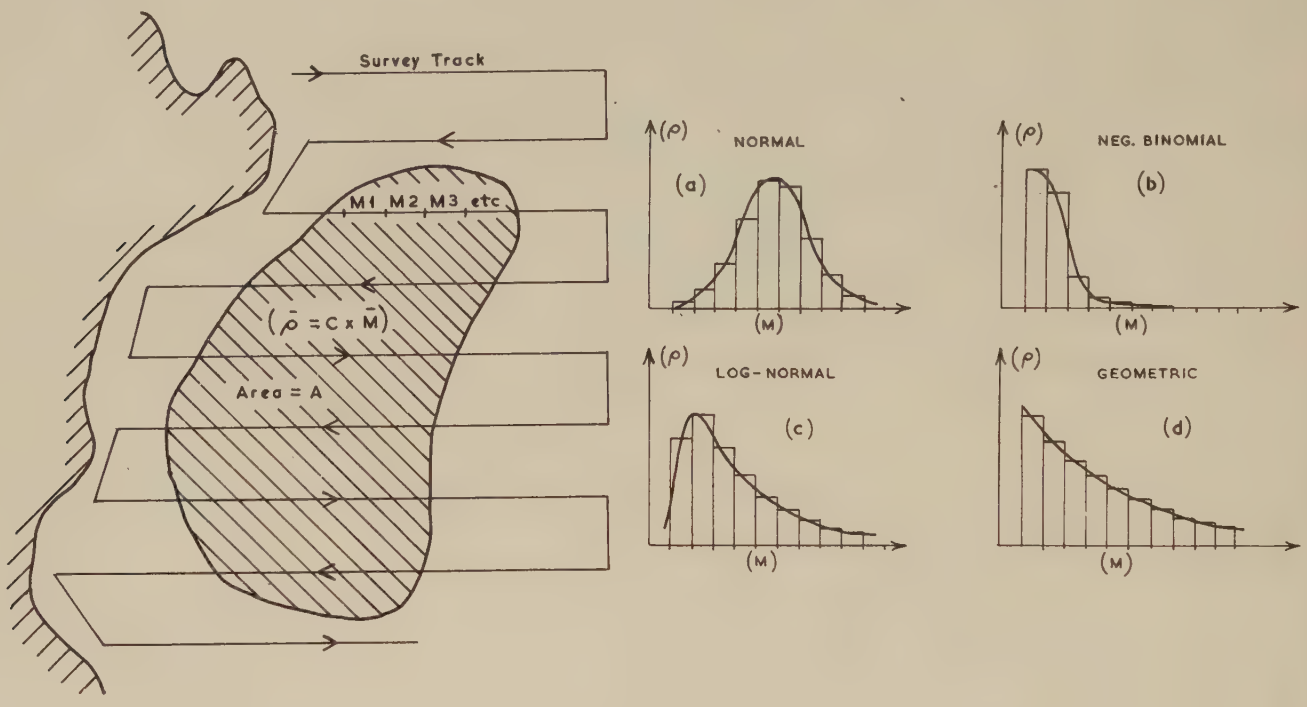
In summary: Measurements of absolute densities with echo-integrators are most commonly achieved by two principal methods. The first is based on experimental calibration using live fish for direct determination of the constant C by the relationship $\rho_A = CM$. Thus, the product of the constant and the observed integrator reading (M) gives a direct estimate of the absolute density. This method is particularly suitable for analog integrators.

The second method is based on mean volume backscattering strength (MVBS) measurements and is suitable for analog and multi-channel computerized integrators. Provided that the principal instrument constants and target strength are known, the density can be calculated from eqn 63.

6.5 Determination of Mean Fish Density in a given Area

In the previous sections we have explained measurement processes that are technical in nature. This section goes a step further and explains how a mean fish density within a given survey area is determined, and how this is a combined technical and statistical problem. Figure 43 below serves to introduce the problem.

Figure 43



It is desired to determine the mean (average) fish density ($\bar{\rho}_A$) in the area A using the survey observations M_1, M_2, M_3 ..... M_N and a calibration constant C. A straightforward procedure would be to calculate the mean from the formula

$$\bar{\rho}_A = C\left(\sum_{j=1}^{j=N} M_j\right)/N \quad \text{(estimated mean)} \qquad \ldots\ldots\ldots\ldots (67)$$

This has the limitation that it pre-supposes the arithmetic mean is valid, i.e. that the 'M' value, treated as a continuously random variable, exhibits a probability density function (PDF) which can be reasonably well approximated by the normal distribution. If that is true and C is an unbiased calibration constant, then the result would be an unbiased estimate of the mean fish density in the area. However, real-life data have demonstrated clearly that a set of M-data yielded by large-scale acoustic surveys is rarely normally distributed. In most cases it shows a highly positive skewness, or else the observations tend to fit the negative binomial (b), a log-normal (c) or even a geometric distribution (d) where the probabilities of occurrence of successively larger

M-values are decreasing geometrically as indicated in Figure 43. Because of this it is important that survey data be submitted to appropriate statistical analyses in order to estimate the most representative mean fish density in the area. A more detailed coverage of the subject is given in section 10.3.

Summary: The determination of mean fish density in a given survey is a combined process of measurement and statistical analysis. The accuracy of the density estimate depends on the accuracy of the calibration constant C, and on the goodness of fit of the probability function on which data averaging is based.

7. CALIBRATION

7.1 Acoustic Calibration

The purpose of quantitative acoustic surveys of fish is to measure their abundance. Accurate repeatable calibrations are fundamental to the overall accuracy of results when estimating the size of a fish stock in this way and the required precision for different types of survey is suggested in Chapter 6.

It is necessary to derive a relationship between the output of an echo-sounder and the fish insonified by its transducer beam. The usual technique for processing echo signals from fish is echo-integration, whereby it is assumed that the acoustic energy received after correction for beam spreading and absorption losses is proportional to fish density. To obtain the constant of proportionality it is necessary to know the overall calibration of the echo-sounder ie electrical and acoustical, in addition to the target strength of the fish. The first two sections of this chapter are concerned with methods for acoustic calibration only. The factors involved are the acoustic source level, (SL) the transducer receiving sensitivity (SRT) and the equivalent beam factor of the transducer Ψ. In later sections overall system calibration is considered.

Some common factors to successful acoustic calibration are:-

(a) Always try to work in free-field conditions. Within the range of the calibration there must be no effect from boundaries, ie surface or bottom of the water, ships hull, mooring structures etc. The water should be homogeneous and also isotropic, ie having the same properties in any direction.

(b) Knowledge of the water temperature and salinity to correct for absorption losses (Figures 9, 10 a,b,c) so that a calibration for the water path of the acoustic pulses can be made.

(c) An exact measurement of distance between parts of the system for some calibration methods and a knowledge of the speed of acoustic waves (Figure 8) to measure the transit time of pulses.

(d) Transducer measurements can only be made reliably in the 'far-field' unless special acoustic field-sampling techniques for near-field measurement can be applied. Within the near-field large fluctuations of pressure maxima and minima occur (Figure 19) due to the difference in distance to the various parts of a transducer face from a particular point in its field. The minimum distance to which the near-field extends has been defined in eqn. 16, it is also the

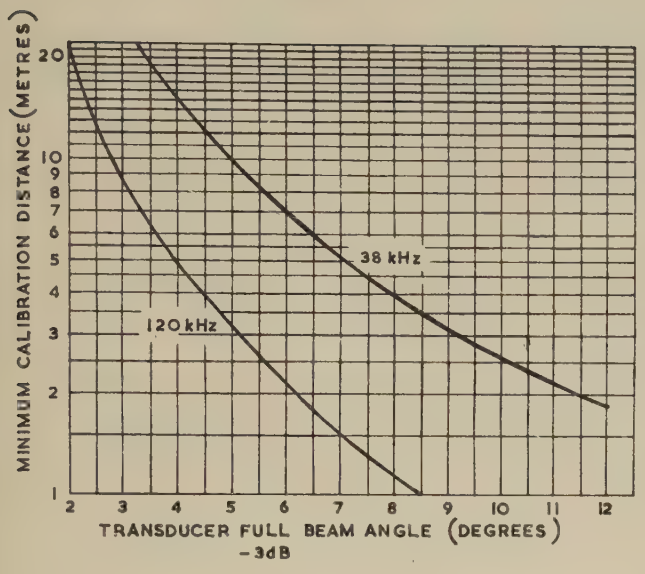
$$\text{Minimum calibration distance} = 2L^2/\lambda$$

where L = the length of the longest side or diameter of the transducer face

λ = wavelength of the echo-sounder

both of these in similar units ie mm or m.

Figure 44



Thus, the narrower the beam (long transducer), the greater the distance of the near-field, see Figure 44 for practical distances at 38 and 120 kHz.

(e) Calm water conditions are very important. Relative movement of any parts of the acoustic system during calibration can lead to extreme fluctuation of the signals.

(f) Noise from whatever source must be very low at the calibration site. It quickly becomes obvious when the presence of noise is preventing a satisfactory calibration.

(g) It is essential that the survey transducer is tuned to be resistive at the echo-sounder operating frequency (this should be the natural resonant frequency of the transducer). Then the transducer plus cable should be tuned to be resistive at this frequency. The principle of this operation is given in section 7.2.1. When tuning is correct, the transmitter is connected to the transducer alone and the power measured. Then, with the cable re-connected the power is measured again and from the two measurements the power loss due to the cable is calculated.

The value of the absorption loss α is sufficiently low at 38 kHz that for short ranges it is insignificant, so when calibrating acoustic survey systems α can usually be ignored at this frequency, (0.0087 dB/m when the temperature is 5°C and decreasing as the temperature increases). At a range of 12 m, the likely error through ignoring α would be 0.1 dB, and the specified target strength of standard spheres for calibration is now claimed to be within ±0.1 dB. At 120 kHz, matters are much more difficult. When t = 22.5°C, α = 40 dB/km, or 0.04 dB/m, so the absorption loss would be 0.1 dB at 2.5 m.

7.1.1 Standard Targets

The principle of placing a known target, with an accurate and reliable target strength, on the axis of the beam, at a specified distance from the transducer can be used to obtain a combined figure for SL + SRT, ie the source level and receiving sensitivity, respectively. This method avoids the use of calibration projectors and hydrophones, or relying on electrical measurements, then calculating SL and SRT from formulae. It does require very accurate alignment of the target on the acoustic axis of the beam and the calibration only refers to this axis unless the beam pattern is known.

The following expression is used to obtain SL + SRT when a standard target is available.

$$SL + SRT = VRT + 2TL - TS \quad \ldots\ldots\ldots\ldots\ldots \quad (68)$$

where SL = source level in dB/1μPa/1m

SRT = sensitivity of transducer in dB/1V/1μPa

VRT = voltage at the transducer due to standard target echo in dB/Volt

TL = transmission loss in dB, i.e. 20 log d + αd

d = distance between transducer face and target

TS = target strength of calibration sphere in dB.

Apart from the echo-sounder and standard target only an oscilloscope is needed to complete the equipment for this form of calibration. However, when an overall survey precision to ± 0.5 dB is necessary, great care must be taken to ensure that no error is introduced into the calibration experiment. The difficulty lies mainly in the suspension and the alignment of the standard target on the axis of the beam in the far-field. Of course, since the detailed or other necessary arrangements will vary according to the whereabouts of the transducer, it may be more difficult to perform a calibration on a hull-mounted transducer than one fitted in a towed body unless special handling equipment is available.

It is hard to make any form of attachment to a sphere without affecting its acoustic properties. A very fine mesh nylon net bag without knots is the preferred method of holding the relatively small solid copper or tungsten carbide spheres now advocated, (Foote, 1982). Fine mono-filament nylon line can then be used as the suspension material because it cannot trap air, having no interstices.

The spheres recommended for calibration purposes are:

30.4 mm diameter copper sphere with a TS of -40.7 dB at 38 kHz.

38.1 mm diameter tungsten carbide sphere having a TS of -42.4 dB at 38 kHz.

These standard targets are relatively insensitive to temperature changes, small deviations in frequency and change in pulse duration from 0.5 to 1.5 ms.

Ensuring that the target is on the acoustic axis of the beam can prove to be a difficult task. It is usually necessary to arrange for carefully controlled movement of the target in the beam to be sure that the maximum signal is obtained. This will entail a three-point suspension to prevent the target swinging excessively, which would cause the echo-signal to fluctuate. If the transducer is hull-mounted, three hand winches are required and must be operated with some precision to achieve correct positioning. The rigging for measurements can be a critical procedure which requires careful planning and execution. Foote et al. (1981), give the following description of such an exercise:

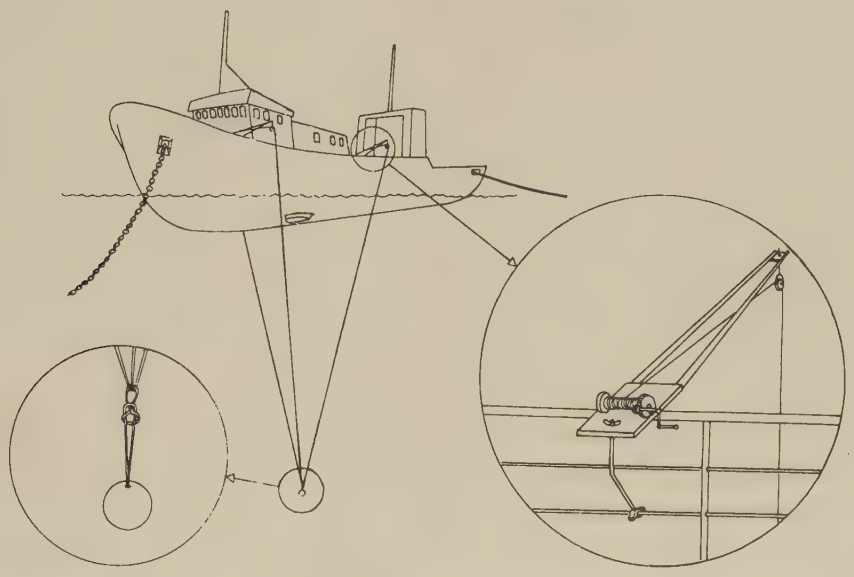
"The vessel is ideally anchored in calm and sheltered water with a depth of about 50 m. For stable measurements the stern should be tied to land or anchored." This is illustrated in Figure 45.

"Winches to guide and steer 3 lines to the sphere to centre it in the echo-sounder beam are affixed to the deck rails. This is done in accordance with detailed ship drawings. Winch No. 1, is placed in the transverse plane of the ship running through the transducer. The second and third winches are placed on the opposite side of the boat and

at equal distances from the transverse section containing the transducer and winch No. 1. Each winch is provided with a long spool of 0.60 mm - diameter, monofilament nylon marked with small lead weights at five-metre intervals, beginning 10 m from the loose end.

Prior to commencing the sphere measurements, the lines from winches 2 and 3 are drawn beneath the hull to the other winch by means of a line passed under the keel before anchoring.

Figure 45



Measurement configuration and sphere suspension during a calibration exercise.
(Illustration from FOOTE et.al. 1981)

The appropriate sphere with affixed loop is attached to the three suspension lines, Figure 45. It is then immersed in a solution of soap and fresh water to clean and de-aerate its surface before being lifted overboard by the attachment lines without being touched by hand. The sphere is lowered beneath the vessel to the desired depth, for example, 25 m, determined roughly by counting the lead marker-weights on each line." In fact a range of only 5 m may be satisfactory so long as the target produces a 'clean' echo which is in the far-field (see Figure 44) and the accurate T.V.G. range.

For proper centering of the target, "The sphere is moved on to the acoustic axis of the transducer by adjustment of the several winches. This operation is coordinated by one person observing the echo waveform on an oscilloscope. The centre is reached when the slightest movement of suspension line either in or out results in a decrease in the echo signal".

The distance from transducer to the sphere is obtained by measuring the transit time of the pulse in milliseconds (ms) observed on an oscilloscope i.e. from start of transmission pulse to start of the sphere echo-signal. Using the appropriate speed of acoustic waves c, (Figure 8) the distance d, is calculated from d = c x time/2.

An example of a standard target calibration is given below.

Step 1 Make sure that the target is on the axis of the beam and that the signal is not fluctuating significantly

Step 2 Avoid close proximity of the target to the transducer, measure distance d

Step 3 Measure the peak-to-peak voltage of the signal from the target

Step 4 Convert the peak-to-peak voltage to an rms voltage (see section 2.3)

Step 5 Calculate SL + SRT from equation 68.

If we assume a distance, d of 3.56 m for (2) and a voltage of one volt for (4) when the target has a TS of -20 dB. In this example α is ignored.

$$SL + SRT = VR + 2TL - TS$$
$$= 20 \log 1 + 40 \log 3.56 - (-20)$$
$$= 0 + 22 + 20$$
$$= 42 \text{ dB}$$

Thus the system may be calibrated without knowing the individual performance of either the transmitter or transducer. There is a need to be cautious about the signal voltage measurement because of the practical difficulty of making such a measurement directly across the transducer terminals or the cable of a towed transducer. The problem is two-fold, the usual inaccesibility of the terminals, but there is also distortion of the oscilloscope trace caused by the high voltage of the transmission pulse in relation to the small signal voltage being measured.

A practical alternative is to use the calibrated signal output of the receiver amplifier (VR) because the transmission pulse is reduced to an acceptable level in the early stages of the amplifier. In this case the gain law (TVG) and any 'static' gain must be known very accurately at the range of the target, because the rate of change is very large at short range. Static gain (SG) is defined as any gain switched into the receiving system which is not part of the actual Time Varied Gain.

If the TVG system gain is known precisely at the calibration range, TL can be omitted from eqn 68 but any static gain must be subtracted, ie
$SL + SRT = VR - SG - TS$. A summary of the main factors to be considered in relation to standard target calibration, i.e. their advantages and disadvantages is given below

Advantages

a) The method is relatively simple and reliable now that accurate standard targets are easily obtainable.

b) A standard target is free of acoustic noise and fish behaviour problems which can be troublesome when calibrating on live fish targets.

c) Because of the repeatability of the method, it can be used for accurate monitoring of performance changes in the overall system.

d) Inter-ship calibration can be carried out irrespective of geographic position.

Disadvantages

a) The method cannot take into account the beam pattern.

b) It may be difficult to align the standard target on the acoustic axis, especially with hull-mounted transducers. Needs very calm water, practically free of current. The vessel may also have to be anchored both from the bow and stern to avoid

undesired movements. This problem can be significantly reduced when a dual beam method is used.

c) In practical calibrations it has been noted that fish are attracted by shiny standard targets, particularly tungsten carbide balls so care must be taken to avoid fish spoiling the calibration.

Calibration by standard target can include the receiver amplifier. In this case the combined calibration parameter becomes

SL + VR, where VR = SRT + G

G is the effective amplifier gain in dB.

However, the entire system includes the echo-integrator so an overall calibration should be related to the output, M mm of deflection, of this instrument.

$$10 \log M = SL + VR + TS - TL + c\tau/2 + 10 \log G_i \quad \ldots\ldots\ldots\ldots (69)$$

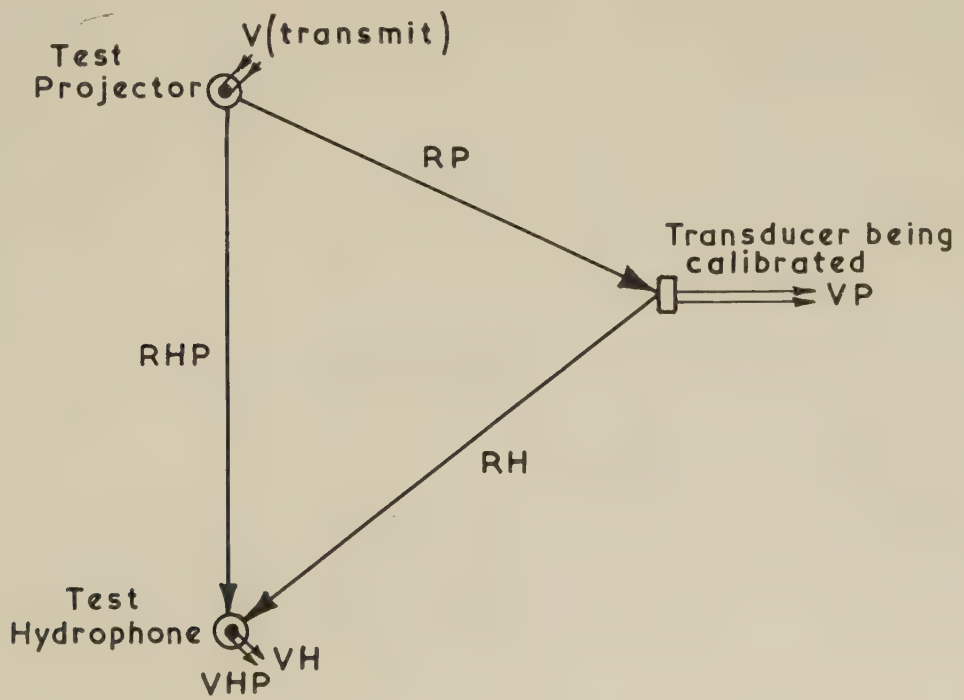
G_i is the integrator gain.

7.1.2 Calibration by Range (R) and Voltage (V) measurements

This method by Robinson and Hood (1982) is only suitable for the calibration of transducers in towed bodies. In addition to the survey transducer mounted in its towed body with the towing cable connected it is also necessary to have a projector and a hydrophone. It is <u>not</u> necessary to know the characteristics of the projector or the hydrophone, neither do they need to be reciprocal devices.

The three components of the calibration: projector, hydrophone and survey transducer must be placed in a triangular formation, one at each point of the triangle, Figure 46. They must be at the same depth; the survey transducer must be mounted so that it can be rotated to transmit to the hydrophone, and the projector arranged so that it can be aligned to transmit to the hydrophone.

Figure 46



The procedure is as follows:

Step 1 survey transducer transmitting to hydrophone: measure the voltage received at the hydrophone, convert to rms, call this VH.

Step 2 switch off the survey transducer.

Step 3 transmit from projector to the hydrophone, measure the received voltage (VHP), convert to rms, call this VHP.

Step 4 rotate projector into alignment with the survey transducer and measure the voltage received, convert to rms, this is VP.

Step 5 note the exact range between the survey transducer and the hydrophone RH; the range between the projector and the hydrophone RHP; the range between the projector and the survey transducer, RP.

Step 6 obtain a figure for the absorption loss α.

It is then possible to calculate SL + SRT.

$$SL + SRT = 20 \log(VH.VP)/VHP + 20 \log(RH.RP)/RHP + 2\alpha(RH+RP-RHP) \quad \ldots\ldots\ldots\ldots (70)$$

As with all similar measurements of voltage and range it is essential to ensure that the test equipment is precisely calibrated and that extreme care is taken in reading the oscilloscope.

7.1.3 Hydrophones/Projectors

Calibration against known hydrophones and projectors is not a preferred method in fisheries acoustics because of the lack of stability with time of these devices. The use of hydrophones and projectors is included for completeness and as a guide to measuring the separate performance of transmitting and receiving systems.

Hydrophones and projectors have known calibration factors which when these devices are used to measure energy transmitted from an echo-sounder, or to transmit to the echo-sounder, can be used in a form of the acoustic equation to obtain the equipment calibration. Although the same device may be used for both receiving and transmitting, this practice is not recommended for the calibration of fisheries acoustic equipment. Ideally, the calibration device should be rigidly fixed in relation to the face of the transducer to be calibrated, but with the need to observe a minimum distance between the two, to ensure that operation is in the far-field, Figure 44, this may pose a difficult problem.

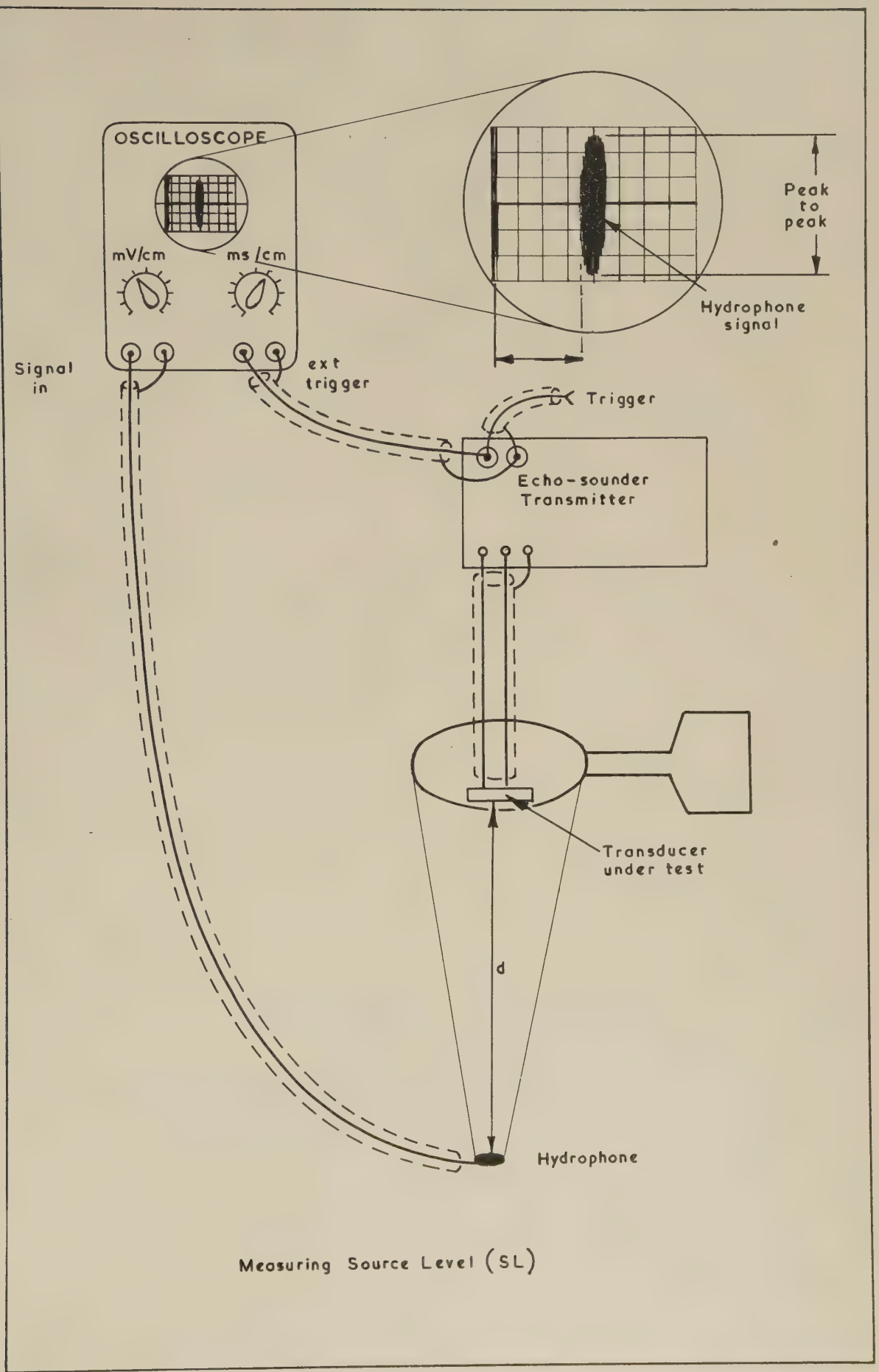
Measurement of Source Level (SL)

This measurement requires the following items.

1. Calibrated hydrophone complete with sufficient length of cable.
2. Oscilloscope.
3. Temperature measurement.

It is assumed that the echo-sounder transmitter is set to normal pulse duration (as used for survey) and standard power output. The general arrangement for this type of calibration is shown in Figure 47 and the principle is applicable to hull mounted as well as towed transducers. As the distance (d) between the transducer face and the hydrophone

Figure 47



Measuring Source Level (SL)

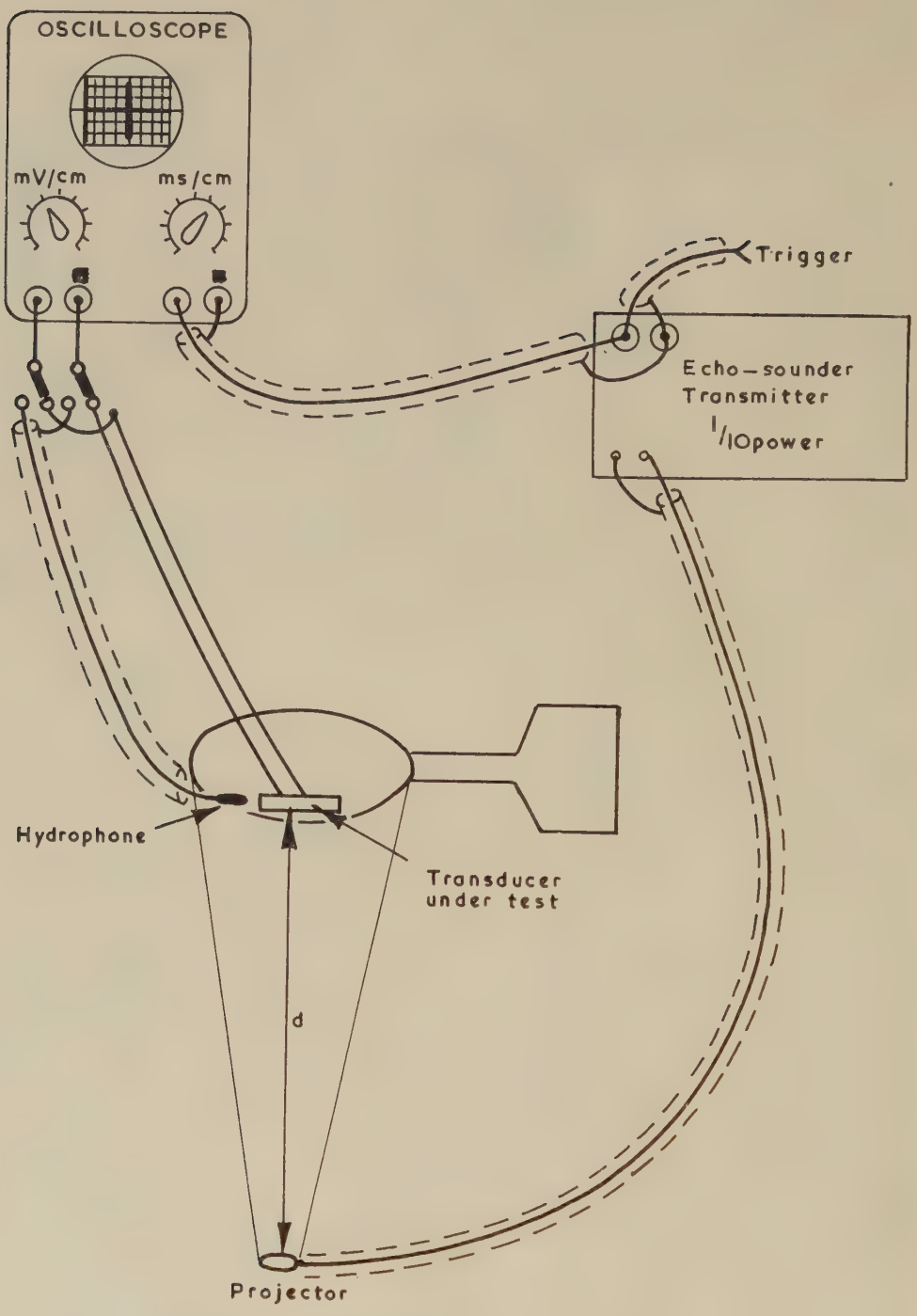


Figure 48. Measuring SRT

(A) projector SL NOT known

is known, a time base setting for the oscilloscope can be calculated assuming an acoustic speed of 1500 m/s i.e. 1.5 metres/millisecond

if d = 3 metres time = 3/1.5 = 2 ms, then the timebase speed could be set at about 0.5 ms/cm. Having once set the timebase coarse control to put the signal into a suitable position on the CRT and checked that the timebase is in calibrated mode, the precise time to the beginning of the signal is read off. The true depth, range or distance for calibration is d = c x time where c = speed of acoustic waves (c must not be assumed to equal 1500 m/s). The speed should be obtained from Figure 8 when the temperature and the local salinity have been measured.

Example: t = 10°C, S = $30^{o}/oo$ so c = 1482 m/s

assuming the actual time read from the oscilloscope timebase is 2.4 ms, the true distance is calculated as $d = 1482 \times 2.4 \times 10^{-3} = 3.56$ metres.

If the received pulse is 3.4V peak-to-peak, we see from section 2.3 that it must be converted to rms as follows: $(3.4/2) \times 0.707 = 1.2\ V_{rms}$ then converted to dB/Volt, i.e. 20 log 1.2 = 1.58 dB/V.

The source level of the echo-sounder can now be calculated

$$SL = VRT - SRT + 20 \log d$$

it is assumed that α can be neglected, but this is not always the case.

where VRT = hydrophone output voltage in dB/V

SRT = hydrophone sensitivity from its calibration graph (in dB/Volt/1μPa)

d = distance between hydrophone and transducer in metres

SL = source level in dB/1μPa/metre

Assuming a figure for SRT of -208.5 dB/V/1μPa

$$SL = 1.58 - (-208.5) + 20 \log 3.56 = 210 + 11$$

$$SL = 221 \text{ dB/1}\mu\text{Pa/m}$$

For measurements made at angles to the acoustic axis the source level will be lower. Accurate results with the echo-integration technique require a true beam pattern to be measured at a sufficient number of points in each plane to produce a three-dimensional plot. This requires very special facilities and manufacturers figures for beam angles must normally be used to calculate a figure for Ψ. The on-axis source level is used in the final calculation of biomass.

For the simplest method the test hydrophone used for SL measurement is transferred to a position close to and in line with the face of the survey transducer under test (not over its face). A projector is then fitted in the position previously occupied by the hydrophone, see Figure 48. This projector is supplied with a suitable drive voltage at the correct frequency and pulse duration. It is not necessary to know the projector calibration nor the amount of power applied to it for this method. The procedure is as follows:

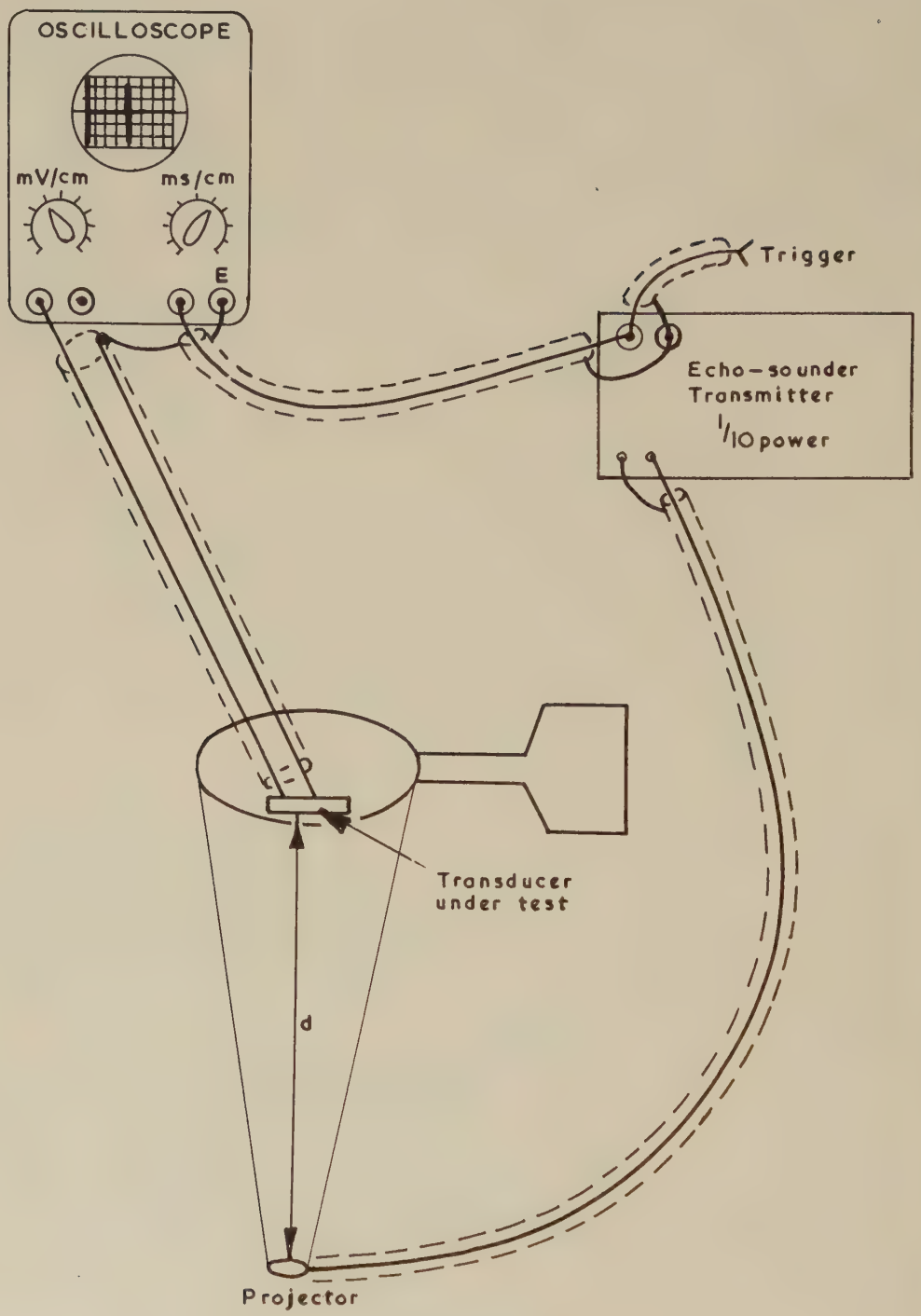
Step 1 From the oscilloscope read the peak-to-peak voltage received at the terminals of the echo-sounder transducer under test, call this V_1, assume V_1 = 18 mV

Step 2 Let the voltage measured across the hydrophone terminals = V_2

V_2 = 0.6 mV

Step 3 Take the ratio $V_1/V_2 = 18/0.6 = 30$ 20 log 30 = 29.54 dB.

Measurement of Receiving Sensitivity.



Measuring Receiving Sensitivity (SRT)
Figure 49. Measuring SRT (B) when the projector source level (SL) is known.

(B) projector SL known

We know that the hydrophone SRTh = -208.5 dB/V/1μPa and from the measurements above it is clear that the survey transducer is 29.54 dB more sensitive than the test hydrophone.

SRT = SRTh + 29.54 = -208.5 + 29.54 = -178.96 dB/V/1μPa

Measurement of Receiving Sensitivity. Method (B)

This method does not require the test hydrophone but the source level of the projector SLp must be known, or obtained. Calibration is usually presented in the form where a given driving voltage, or current, applied to the projector, will result in a particular source level.

ie XdB/1μPa/metre/per Volt or Amp

(current is more difficult to measure accurately than voltage).

The physical arrangement for the calibration is shown in Figure 49. If the test projector does not have its own transmitter, take the following steps:

Step 1 disconnect the echo-sounder transmitter from the survey transducer

Step 2 connect this transmitter to the test projector

Step 3 before switching the transmitter ON, reduce power to at least 1/10 of normal.

SRT of the survey transducer = VRT + 20 log d - SLp ..... (71)

A typical calibration figure for the test projector might be 120 dB/1μPa/m/V.

If the rms voltage from the transmitter is 30V

SLp = 120 + 20 log 30 = 149.5 dB/1μPa/m

The oscilloscope is then used to measure the voltage received across the terminals of the survey transducer, eg 26.7 mV, peak-to-peak.

V_{rms} = (26.7/2) x 0.707 = 9.4 mV

VRT = 20 log 9.4 x 10^{-3} = -40.5 dB/V

SRT = -40.5 + 20 log d - 149.5

if d = 3.56 m, 20 log d = 11 dB

SRT = -40.5 + 11 - 149.5 = -179 dB/V/1μPa.

It should be noted that section 7.1.3 is included so that all of the calibration methods can be understood. Although they suffer from the inherent poor stability of wideband devices, the test projectors and hydrophones do allow a separate assessment of receiving and transmitting characteristics of the survey transducer to be made.

7.1.4 Intership Acoustic Calibration

In the previous sections of this chapter we have looked at methods for the calibration of parts of the survey system, or the complete system. Despite great care in making these calibrations it is often uncertain how the results from one vessel compare with those of another. Now that electronic units are very stable and standard targets of high accuracy are available for on-axis calibration it should be possible in theory to obtain very close agreement between acoustic survey systems on different ships. One problem is lack of knowledge of the <u>actual</u> beam pattern, a vitally important factor for the echo-integration technique. The concept of checking calibration of the complete acoustic equipment i.e. echo-sounder and echo-integrator on one vessel against that of

another is simple and attractive in principle but it contains practical difficulties.

It would be ideal if the vessels could travel side-by-side over an area of static targets whose numbers (density) increased or decreased gradually along the survey track. This would allow direct comparison of results over the full dynamic range of signals entering the echo-sounder. Such a situation is not possible and for intership calibration we must consider the following factors.

1. Is there a suitable fish stock aggregated at a moderate density over a significant area (several nautical miles)?
2. Are the fish likely to be scared?, e.g. are they too close to the surface? (the effect of scaring may be small but variable from ship to ship).
3. If the fish are in discrete schools how large and how mobile are these? These questions are particularly important if schools are scarce, one vessel may sample a significantly different part of the school to the other vessel, simply because of the time lapse or distance between them.

Intership calibration procedure is commonly carried out for the purpose of comparison, or the direct transfer of results from one accurately calibrated research vessel to another vessel (or vessels). This is desirable because experience shows that considerable time, effort and repeated testing is necessary before the engineer/scientist is satisfied with the level of accuracy and stability he wants to attain with calibrations prior to actual fish density measurements at sea. In the case of multi-ship surveys the question of accuracy may not predominate, and inter-ship calibration may merely compare different equipments to establish a consistent and reliable data collection for subsequent analysis and the plotting of charts showing relative abundance of fish. An intercalibration between two or more vessels is based on the fundamental assumption that the respective acoustic systems are

(a) echo-sounding on the same fish aggregation

or (b) echo-sounding on an equivalent sea bed.

i) Inter-ship calibration on fish layers

This has been practised for some years especially by the Institute of Marine Research, Bergen, Norway (Røttingen, 1978). Also, Icelandic and Norwegian research vessels have intercalibrated on dispersed fish concentrations as part of a joint survey of the Icelandic capelin stock (Vilhjalmsson et al., 1982). Such calibrations have occasionally been carried out in FAO projects since 1973 although not reported. Using the same notation as before, the mathematical basis for the intercalibration is

$$\bar{\rho}_{A_c} = C_c \bar{M}_c \qquad \ldots\ldots\ldots\ldots (72)$$

$$\bar{\rho}'_A = C' \bar{M}' \qquad \ldots\ldots\ldots\ldots (73)$$

On the assumption that: $\bar{\rho}_{A_c} = \bar{\rho}'_A$, i.e. both vessels will on average measure equal fish density, the scaling factor for the non-calibrated vessel can be calculated directly

from

$$C' = C_c \, (\bar{M}_c / \bar{M}') \qquad \ldots\ldots\ldots\ldots (74)$$

In other words the vessel subjected to calibration will have a scaling factor (C') which is equal to the scaling factor (C_c) of the pre-calibrated vessel after multiplication by the ratio between mean integrator values ($\bar{M}_c/\bar{M}'$). Thus, two factors become apparent (a) the validity of this kind of inter-ship calibration depends entirely on the fish stock, ie if its geographic extent and dispersion permits $\bar{\rho}_{A_c} = \bar{\rho}'_A$

(b) if the M-values obtained are wide ranging, the simple arithmetical mean ($\bar{M}$) may not be suitable and C' must be established through regression analysis of the data. Røttingen (1981) shows inter-ship calibration results between R.V. G. O. SARS and R.V. JOHAN HJORT, first using a standard copper sphere and subsequently repeated on a scattering layer of capelin in the Barents Sea. Differences in results varying from approximately 17-23% depending on the depth of the different fish layers are discussed but not satisfactorily explained. An overall appraisal of the results gave the two calibration methods equal weight and 'C' was taken as the mean value of both experiments.

An example of good calibration results is presented in Vilhjálmsson et al. (1981) and illustrated in Figure 50a and b. The wide spread in M-values is clearly demonstrated so the data are well adapted for regression analysis. A confidence interval for the estimated ratio ($M_{GOS}M_{BS}$) is not given but a high correlation (r = 0.98) points towards a relatively high-precision inter-ship calibration.

The field procedure for the inter-ship calibration can be summarised by three steps

Step 1 Locate the target stock and determine the time of the day when its distribution pattern is suitable

Step 2 Put all equipment in to normal operational mode as for actual survey work

Step 3 Run the two vessels at a fixed inter-ship distance and over a sufficient area (or length of time) obtain representative sets of M-data.

In regard to (3) optimum vessel speed should be determined and the geometry of the inter-ship positions related to the experimental aim. If close simulation of survey conditions is important the vessel's speed should be the same as during a normal survey. This would dictate a larger inter-ship distance (to avoid undesired effects of noise and vessel wakes and to maintain navigational safety). But, the possibility of the two vessels insonifying the same, or equivalent, fish layer(s) would be reduced. There are conflicting criteria and optimum arrangements can only be established on the basis of repeated field experiments. Success of such experiments depends on several factors, the vessel size and noise level, depth distribution of the fish layer, geographic extent and mobility of the fish stock; its biological characteristics and sensitivity (fright reaction) to a moving vessel, as well as weather and sea conditions.

Fig. 50 (a) Integrator values vs. distance. 4 August 1979

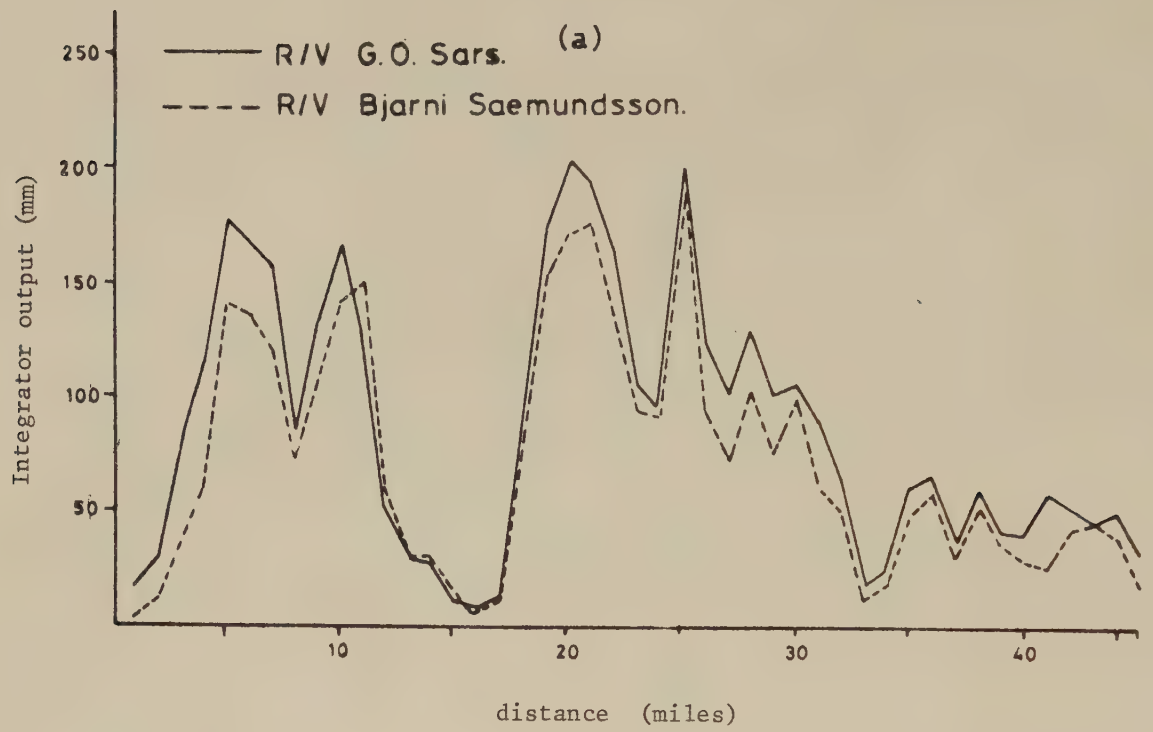


Fig. 50 (b) Linear regression of integrator values. October 1981

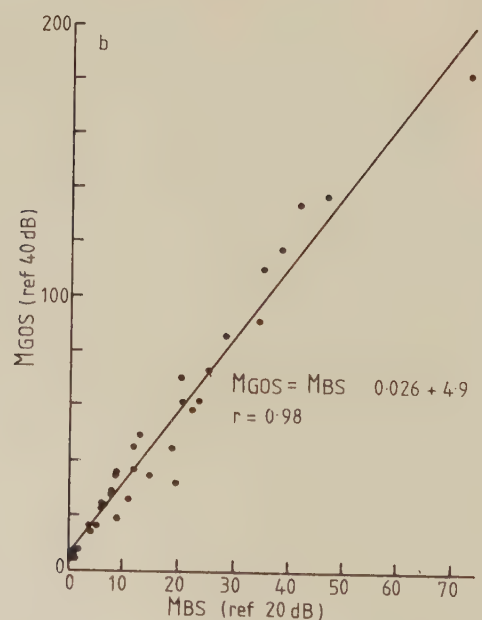
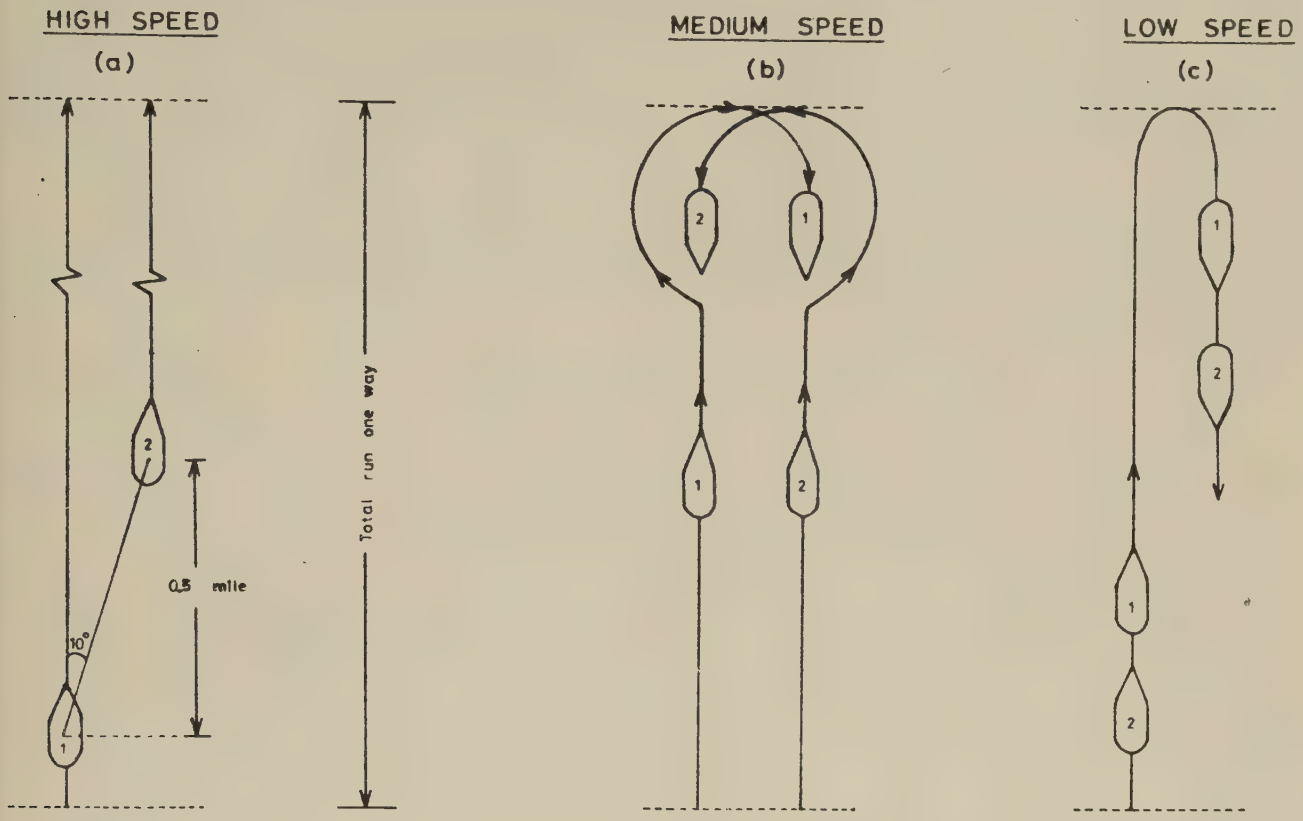


Fig. 51 Alternative sailing arrangements suggested for intership calibration on scattering layers of fish



As an approach to the experimental design, three different inter-ship sailing patterns are illustrated in Figure 51 and relate to different vessel speeds; (a) appears to give best results in Norway (Røttingen, 1982); (b) may give good results for smaller vessels and when the target stock is relatively stationary; (c) refers to a situation when the available fish layer has a very limited geographic distribution and may have to be criss-crossed several times to obtain the necessary data. The purpose of reversing

vessel positions is to check if vessel noise and possible wake effects will influence the measurements. Compared to the standard target calibrations this method has the advantage that it utilizes natural targets in real-life survey conditions and it includes all equipment parameters. It can be used to intercalibrate two integrator systems of different frequency. However, the two vessels do not integrate exactly the same targets so the assumption of equal densities may, or may not, be justified.

ii) Inter-ship calibration on the sea-bed echo

The nature of the sea-bed as an acoustic scatterer is described in Urick (1975). As a 'standard target' for inter-ship calibration (or transducer comparison) it is attractive for the following reasons:

a. it is an effective reflector and acoustic scatterer
b. little or no frequency dependance appears to exist for 'rock', 'sand and rock', and 'silt and shell' bottoms
c. different depth ranges or even variable depths can be selected
d. normally, it can be considered a stable echo reflector for months or years
e. it has practically no geographic limits.

Published results on the use of the sea-bed as a target for intercalibration purposes are few. However, this type of calibration has been practiced over the years in FAO projects, for example in the FAO/NORWAY Regional Acoustic Research Centre for Latin America, based in Lima, Peru from April 1975 to August 1980. Numerous comparative calibrations of transducers were made with the sea-bed as a reference target and also to determine the difference in performance of two integrator systems alternatively switched to the same tranducer.

Experience from these calibrations suggests that because of the relatively low (say, 8-16%) coefficient of variation associated with bottom echo integration (and hence independence of geographic variability within a properly selected calibration area) the sea bed is a useful 'standard target'. It is suitable for the intercalibration of two transducers, two integrator systems using the same transducer, or two, or more ships. The data collected by the FAO/NORWAY Centre did not permit detailed quantitative analysis of the relative merits of the different targets (spheres, natural fish distributions, caged live fish and the seabed), but it did greatly encourage the use of the seabed as one approach to inter-ship calibration. Some examples are given below:

Example 1: Inter-transducer Calibration in Indonesia

Place: Bitung Harbour, North Sulawesi Vessel: R.V. TENGGIRI

Date : April 29, 1982 Target: Seabed echo from 23-27 m

EKS-120 echo-sounder		QM-MK-II Integrator	
Gain	: -20 dB/20 log R	Gain	: 20 dB
Pulse	: 1.0 ms	Expander	: x 10
Power	: 1/1	Range gate	: 23-27 m
Range	: 0-50 m	Others	: as proper and convenient

Results

External Transducer (120 kHz, 10 cm Ø)				Ships's Transducer (120 kHz, 10 cm Ø)			
Channel A				Channel B			
Obs. (No.)	M (mm)	Obs. (No.)	M (mm)	Obs. (No.)	M (mm)	Obs. (No.)	M (mm)
1.	516	9	508	1	306	9	350
2	515	10	562	2	375	10	348
3	437	11	472	3	327	11	348
4	467	12	480	4	332	12	334
5	443	13	512	5	337	13	315
6	479	14	473	6	354	14	310
7	523	15	503	7	408	15	369
8	494			8	364		
Mean value: $\bar{M}_1 = 492.3$				Mean value: $\bar{M}_2 = 345.1$			
Coeff. of variation: C.V.=6.6%				Coeff. of variation: C.V.=7.8%			

The external transducer suspended on a nylon rope was lowered into the water close to the front of the hull-mounted transducer so as to give exactly the same depth sounding. These transducers were alternatively switched to the echo-integrator system to obtain comparative integrator values corresponding to 500 soundings, controlled by an electronic counter.

It was noted that during the measurements the vessel was slowly moving over the bottom about its anchor chain so, for practical purposes, the assumption can be made that the two transducers were sounding on the same target. The ratio between the transducers was estimated as

$$R = \bar{M}_1 / \bar{M}_2 = 492.6/345.1 = 1.426$$

a confidence interval for the ratio was calculated from $C.I. = R \pm t \sqrt{Var\ (R)}$

where $t = 2.15$ corresponding to 95% confidence probability and 14 degrees of freedom, and Var (R) is calculated from

$$Var\ (R) = \frac{1}{n\ \bar{M}_2^2} \times \sum M_{1_i}^2 - 2R \sum M_{1_i} M_{2_i} + R^2 \sum M_{2_i} \Big/ n - 1 \qquad \ldots\ldots\ldots\ldots (75)$$

Thus yielding the confidence limits

Upper limit: $R_u = 1.497$ Lower limit: $R_i = 1.355$

corresponding to ± 5% from R = 1.462, suggesting that inter-transducer calibration (or inter-ship) on the seabed can be carried out with fairly high precision. Similar calibrations have been made, e.g. in FAO projects in Peru, Uruguay and Brazil with coefficient of variation (C.V.) ranging from 5-15%.

Example 2: Inter-system calibration on anchovy layer

Place : outside Matarani Harbour, Southern Peru Vessel: R.V. SNP-1

Date : June 9, 1975 Target: fairly uniform anchovy layer, 10-40 m depth

The 120 kHz integrator systems were intercalibrated, one using the hull-mounted transducer while the other was served by a similar transducer in a towed body of the 'Shark' type. The comparative (M) measurements are tabulated below in millimetres.

	1	2	3	4	5	6	7	8	9	10	11	12
System I	114	88	121	128	55	50	103	134	54	72	50	64
System II	56	39	55	102	21	15	78	80	33	43	29	46

From the above data we obtain

$\bar{M}_I$ = 86.1 with C.V. = 37.8% and $\bar{M}_{II}$ = 49.8 with C.V. = 52.2%

$$R = \frac{\bar{M}_I}{\bar{M}_{II}} = \frac{86.1}{49.8} = 1.729$$

In the above case the vessel was steaming at approximately 8 knots and M-readings (mm) were taken every 6 minutes. It is also important to note that pulse durations were the same at 0.3 ms.

When comparing the results of this experiment with those in example 1 it becomes clear that even a fairly uniform fish layer yields much higher coefficient of variation than obtained from seabed calibrations.

Example 3: Inter-system calibration on caged live fish

Place: Islo Lobos de Afuera, Peru Vessel: R.V. TAREQ II

Date : March 21, 1977 Target: live sardine of size range 6-9 cm and density corresponding to 23,670 tonnes/mile^2

A pulse duration of 0.3 ms was used as for the calibration on the anchovy layer (example 2) but each integrator reading was the accumulation of 1000 sounding integrals instead of 576 as before.

	1	1	3	4	5	6	7	8	9	10	11	12
M_{38}	345	365	354	378	375	403	353	284	302	334	352	331
M_{120}	126	138	133	148	143	153	160	153	142	157	161	131

Giving the mean and C.V. values:

38 kHz system: $\bar{M}_{38}$ = 374.9 and C.V. = 9.4%
120 kHz system: $\bar{M}_{120}$ = 145.4 and C.V. = 8.1%

The above values of the coefficients of variation are similar to those obtained from seabed intercalibrations but again much lower than associated with intercalibrations on a natural fish layer. In some areas (e.g. West Africa, data from the FAO/UNDP Regional Fisheries Survey of W. Africa) plankton layers of highly uniform density and thickness are available for intercalibration. While such layers offer low variability, they can only be used to intercalibrate systems of the same working frequencies because their volume backscattering is likely to differ significantly to that of the fish layers of interest.

7.1.5 Live Fish Calibration

There are many problems in the determination of target strength for particular species and size ranges of fish. Complex experiments to make the necessary TS measurements are beyond the terms of reference and often the scope of FAO projects, so a method of calibration has often been adopted which uses a known number, or quantity of fish.. The purpose of this calibration is to obtain the constant 'C' to convert the echo-integrator reading into fish density using the relationship ρ=CM from Midttun and Nakken (1971). Results can then be expressed in tonnes/square mile of sea surface area.

This type of experimental calibration requires careful organisation and preparation; in particular, a net of suitable material (acoustically transparent) and dimensions must be constructed. Through experience a design has evolved which is known as the standard cage, it has a volume of 6 m^3.

Fish must be caught in sufficient numbers and kept in good condition ready for transfer to the 'standard cage' either to start the calibration, or when the density of fish needs to be increased. Success for this type of calibration is critically dependent on fish behaviour, a factor which varies with species and environmental conditions. Fish may need to adapt to a shallow depth, they may be sensitive to strong light, exhibit unnatural swimming patterns, or show distress if they are too roughly handled, or become too densely packed. Regular observation is important to ensure that the measurements do not become unreasonably biassed through behavioural factors. This is often possible by means of underwater closed-circuit television or by direct observation using divers. If the cage is open at the top and it projects out of the water, handling of fish from the keep net into the cage is simplified. A calibration system of this type, using two different frequency echo-sounders simultaneously is shown in Figure 52.

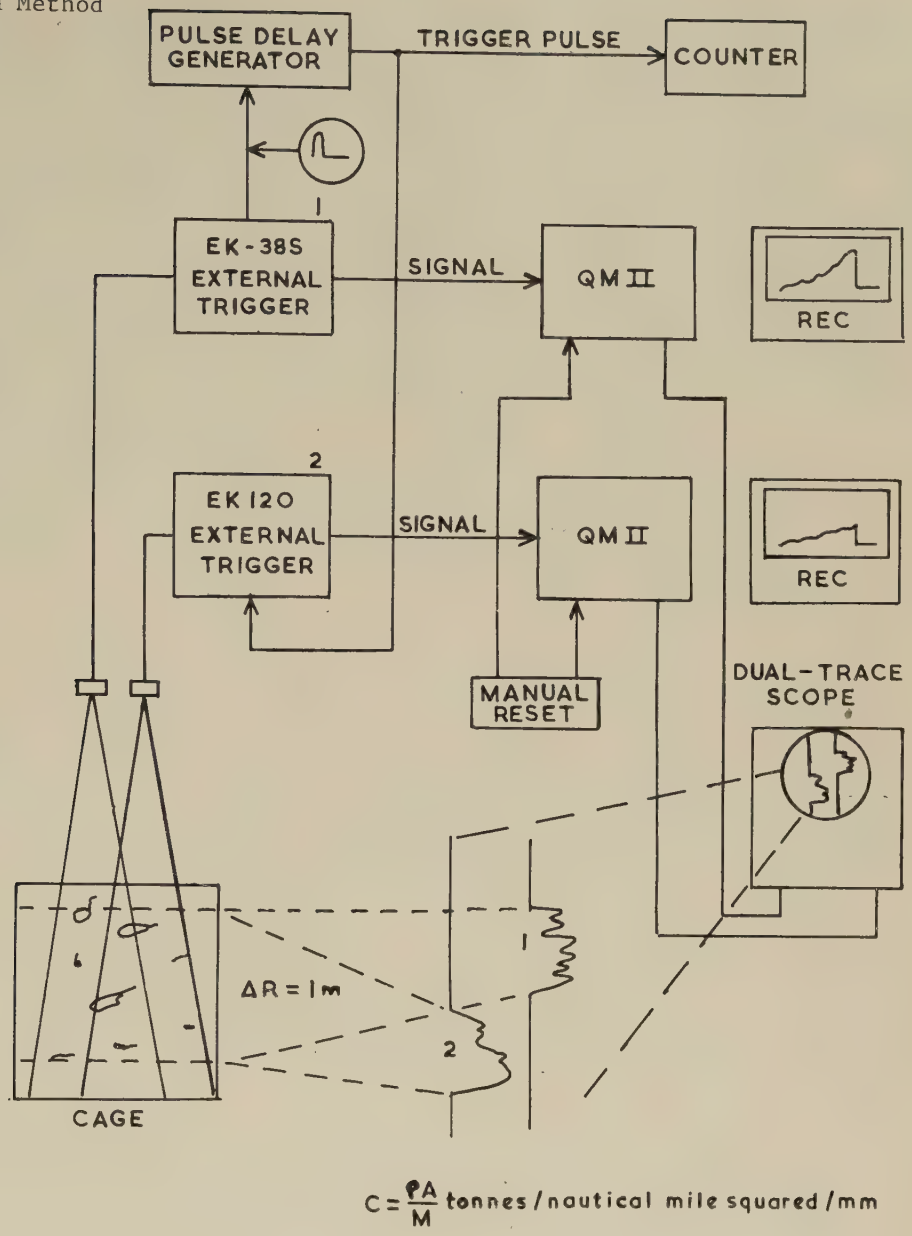
The transducer/s must be fixed with each beam exactly vertical and its axis perpendicular to the centre of the cage. The active face of the transducer must be at a sufficient distance to place the fish targets in the far-field, see Figure 44. Positioning should be such as to avoid any interaction between the main beam (or sidelobes) and

the framework of the cage. This means that the cross-sectional area of the beam, perpendicular to its axis, should be smaller than any internal cross-sectional area of the cage but it should insonify the maximum possible volume within the cage. It is desirable to know the beam pattern so that with slight adjustment of the transducer, up or down, or even tilting, the effect of sidelobes interacting with the framework may be minimised.

The minimum operating range of the TVG is critical; for marine systems it is about 3 m. At short ranges, the rate of change of gain with time is at its greatest so the TVG law must be known precisely, even over the distance of a 1 m integration interval for cage experiments, there is a significant change. Because the greatest rate of change occurs at short range the maximum deviation to the gain/range law is likely and this may lead to serious errors unless taken into account.

Before starting calibration measurements, the instruments must be given time to 'warm up' so that their functions can stabilise, eg timebase, TVG, integrator drift, etc. Then a note must be made of all the control settings, remembering that there may be a need to adjust 'static' gain during the initial test period before starting to run the experiment in order to avoid amplifier saturation.

Figure 52 FAO Calibration Method



$C = \frac{\rho A}{M}$ tonnes/nautical mile^2/mm

Echo-sounder		Echo-integrator	
Gain	dB	Gain	dB
TVG	20 log R	Threshold	
Power	1/1	Depth	m
Pulse	ms	Interval	m
Bandwidth		Speed comp.	10 k
Range	m	Expansion	

If a single set of observations are obtained, the calibration constant Cc is

$$Cc = 3.43\ N\bar{w}\Delta Rc/(vM)\ \text{tonnes/mile}^2/\text{mm}$$

where N = number of fish within the calibration cage

v = effective volume of the cage in m^3

ΔRc = integrator range gate in m

$\bar{w}$ = mean weight of fish in the cage

3.43 = conversion factor to raise km^2 to nautical $miles^2$

M = the integrator reading in mm

In a more general form $Cs = Cc(Sc/Ss)(Pc/Ps)\ 10^{-0.1\ (\Delta Gi+\Delta Ge)}$

in log form $10\ \log Cs = 10\ \log Cc + 10\ \log(Sc/Ss) + 10\ \log(Pc/Ps) - \Delta Gi - \Delta Ge$

where Cs = the constant related to actual control settings during survey.

Sc/Ss = ratio of the number of 'pings' calibration/survey

Pc/Ps = numerical relation between pulse duration, calibration and survey

$\Delta Gi = Gs - Gc$ = difference (dB) in integrator gain, calibration and survey

$\Delta Ge = Gs - Gc$ = difference (dB) in echo-sounder gain, calibration and survey.

Rc and Cc as previously given.

7.2 Electronic Calibration

Calibration of the electronic circuits of the echo-sounder and echo-integrator does not remain constant with time. It is just as important to check these as it is to calibrate the acoustic parts of the system. Electronic calibration checks are in principle easier to perform than those of acoustics because the difficulties associated with water as a propagation medium do not apply.

The test instruments needed for any calibration are discussed in section 3.4 and they will be referred to without further explanation in the following sections. Examples of test and calibration procedures refer to the Simrad EK scientific echo-sounders and the QM echo-integrator but are similar in principle for any equipment of this type.

7.2.1 Transmitter/transducer

The following must be checked to ensure correct functioning of the transmitter.

(a) Transmitter Output pulse amplitude (see (i) below

(b) pulse duration (see (ii) "

(c) carrier frequency (see (iii) "

(d) receiver self noise (measured in position 'test').

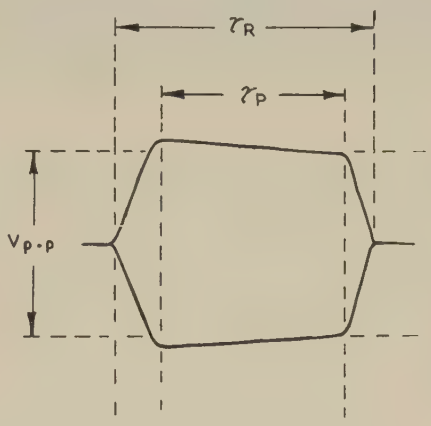
The usual transmitter performance tests are (a, b, c) but (d) is a part of the receiver test procedure, it is mentioned here because a 'noisy' transmitter, especially if it is due to the output stage, may be the cause of a high noise level in the receiver. Even though this fault exists, the transmitter may operate satisfactorily to the specifications measured under points a, b and c. Measurement of receiver noise is given in section 7.2.2.

i) Transmitter output pulse amplitude

Take the following steps;

Step 1 Set the Test/Operate selector to 'TEST' and switch on the echo-sounder. Select longest duration transmitter pulse (a 60 ohm dummy load is connected to the transmitter output in the TEST position). NOTE: The position of the TEST/OPERATE switch should not be changed whilst the echo-sounder is working or the output stage may be damaged.

Step 2 Connect the oscilloscope across the dummy load and measure the voltage Vp-p as shown in Figure 53 below.



Pulse Power Measurement

Typical measured values are

Transmitter output power control	Echo-sounder frequency	
	38 kHz	120 kHz
1/1	35 V_{p-p}	28 V
1/10	10.5 V_{p-p}	9.5 V

The signal is attenuated by about 25 dB, or about 17 times in amplitude before appearing at the TEST SIGNAL socket.

The power may be calculated from

$P = V^2/R$ where V = the 35V measured x 17 to raise to its actual peak-to-peak value. But in order to get the rms value (see section 2.3) the p-p voltage is divided by 2.828.

$V = (35 \times 17)/2.828 = 210.4$ V

$P = (210.4)^2/60 = 737.8$ W

Note: this is the power into the dummy load - not into the transducer.

It is instructive to calculate the change in power for a small change of voltage, eg if Vp-p increases by 2.5 V, P = 847 W.

ii) Measurement and adjustment of the pulse duration

Measure the duration of the pulse in each of the four positions of the 'bandwidth and pulse duration' selector. These should be within ± 5% of the nominal values which should occur within the limits τp to τ_R as shown in Figure 53.

Pulse duration selector Position	Frequency of echo-sounder (kHz)	
	38 or 50 pulse duration (ms)	120
1	0.3	0.1
2	0.6	0.3
3	1	0.6
4	3	1

The pulse duration selector on the Simrad EK model, is marked with the numbers 1-4 as shown in the table. On the EK-R and EK-S models, the control is marked with the nominal

pulse duration. The EK-R and EK-S models are equipped with a trimming potentiometer (R01, PCB 25H43) for adjustment of the pulse duration. This potentiometer affects all four pulse durations in equal proportion. The 0.6 ms pulse is adjusted to its nominal value at the factory and other pulses then normally come close to their nominal values. If separate calibration of each pulse is necessary, the capacitors C104-C107 on the pulse duration selector must be changed.

If it is found necessary to make a correction in the EK model, components must be replaced (R 601 on the transmitter board (PCB 81...6) or C508-C511 on the pulse selector). Changing the resistor value alters all four pulse durations in the same proportion, while replacement of capacitors permits individual correction for each position.

iii) Measurement and adjustment of carrier frequency

The oscillator operates only for sufficient time to produce the transmitter pulse and this has such a short duration that it is not possible to use an electronic counter to measure oscillator frequency directly. Under NO circumstances should the oscillator be forced to run continuously or the output transistors will be damaged. It is necessary to measure the oscillator frequency under normal operating conditions of the echo-sounder, but during any essential adjustment of frequency, no test probes and/or instruments should be connected directly to the oscillator circuit, this is likely to change the operating frequency.

Checking and adjusting the oscillator (carrier) frequency:

Step 1 Set the oscilloscope controls for 'external horizontal' operation. Connect the SG to the external 'X' deflection terminals.

Step 2 Adjust the ouput level from the signal generator and the horizontal sensitivity of the oscilloscope until a horizontal line of approximately 4 divisions is presented on the oscilloscope screen.

Step 3 Position the line in the centre of the screen by adjusting horizontal and vertical position controls.

Step 4 Start the echo-sounder. For each transmission a vertical deflection is observed. Increase the intensity or brilliance, until the flashes due to this deflection are clearly visible on the CRT. If the oscilloscope is equipped with a storage mode this may be used by adjusting the persistence control so that each transmitter pulse is visible for the maximum possible time, but is erased before the next pulse. Be careful to keep the intensity as low as possible to avoid damage to the storage screen.

Step 5 Adjust the vertical sensitivity until the deflection is approximately equal to the horizontal deflection (4 divisions). The trace on the oscilloscope should now be an approximate square appearing once for each transmitter pulse. If, by chance, the frequency of the signal generator happens to be exactly the same as the oscillator frequency, a Lissajou figure is observed Figure 54.

Figure 54

(a) (b) (c)

Step 6 If this is not seen, slowly adjust the frequency of the signal generator, which should be close to the nominal frequency of the echo-sounder, watching the oscilloscope screen. Adjust until the Lissajou figure is as crisp and clear as possible (see Figure 54b and c), when the transmitter oscillator will be equal in frequency to the signal generator. The latter can then be switched into CW mode and measured by the electronic counter. The accuracy of this indirect method of measuring the carrier frequency of the echo-sounder transmitter increases with the duration of the transmitter pulse, therefore the longest pulse duration should be used. Working with extreme care an accuracy of ± 0.05% or better may be obtained.

If adjustment of the oscillator frequency is necessary, take the following steps:

Step 1 Switch off the echo-sounder and wait for 20 seconds.

Step 2 Unplug the transmitter board (PCB 25H43)(EK-71--6).

Step 3 Plug in the extension board in the place of the transmitter and then fit the transmitter board into the socket at the top of the extension board. The core of T01 (EK-T601) is now accessible for adjustment of frequency.

Step 4 Switch on the echo-sounder.

Step 5 Set the frequency of the signal generator to the nominal frequency of the echosounder and then adjust the core of T.01 (EK-601) until the Lissajou figure, as illustrated in Figure 54(c), is obtained.

Step 6 Switch off the echo-sounder and wait for 20 seconds.

Step 7 Remove the extension board and the transmitter.

Step 8 Replace the transmitter board in its original socket.

Step 9 Repeat the frequency check.

Note: It might be observed, particularly with the 120 kHz sounder, that the oscillator frequency alters slightly when the extension board is removed. This may be compensated for by setting the frequency of the signal generator a little to the side of the nominal frequency while tuning the oscillator core. The checking and adjustment procedure is then continued until the frequency is correct with the transmitter in its normal socket.

iv) Transducer

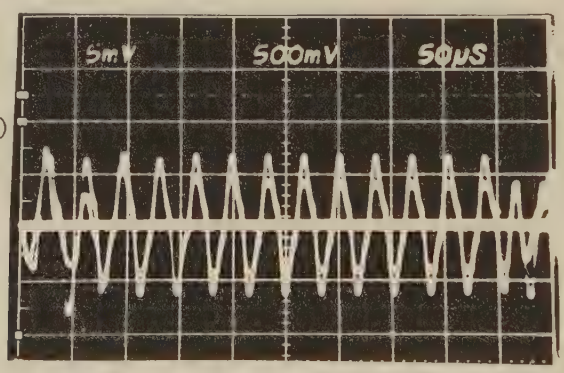
It has already been shown in this section that very little change in voltage output from the transmitter causes a significant change in power output. However, it is also important that the transducer should present a constant loading (which is resistive) to the transmitter. Transducers are electroacoustic devices and the acoustic conditions at the transducer face determine the electrical characteristics which are measured across the terminals. In some instances paint on the face will significantly affect the transducer impedance, changing the amount of power accepted from the transmitter, hence the acoustic source level because the efficiency of the transducer is reduced. A fairing over the transducer face on a towed body can affect the transducer impedance. Magnetostrictive types of transducer need long soaking periods before any form of measurement is made but all transducer faces must be carefully degreased for calibration purposes.

Transducers must be electrically matched to the cable/transmitter combination. This also involves tuning but both processes are specialised and are usually arranged or taken into account by the echo-sounder manufacturers. To check that the matching and tuning are correct it is necessary to know

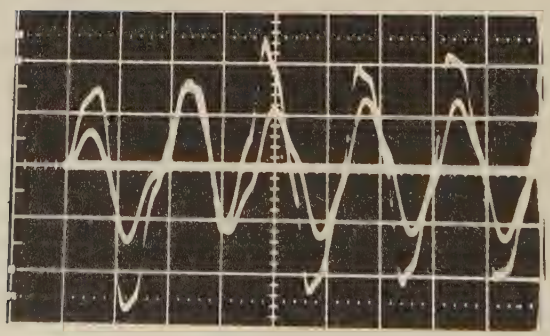
1. that the current and voltage are in phase
2. there is no significant distortion of either waveform.

Photographs of actual waveforms appear in Figure 55 below.

(a)



Superimposed voltage and current wave-forms



Part of (a) expanded

These matters can be seen if the relevant waveforms are compared on an oscilloscope. If the power into the transducer is to be measured the radiation resistance RR, or impedance must be known accurately.

To check 1 and 2 above, obtain current and voltage probes and check that these are matched to the dual input oscilloscope.

Connect the current probe over one of the insulated conductor wires of the transducer cable. Connect the voltage probe across the two conductor wires of the transducer cable. Adjust the timebase/s of the oscilloscope so that both current and voltage waveforms start at precisely the same instant, then examine each individual waveform for distortion. It is difficult to estimate percentage distortion but an attempt should be made to do so and an allowance then made when calculating power. Severe distortion indicates that a fault or faults exist. Next compare the voltage and current waveforms by adjusting their vertical position until one is superimposed on the other. Inspect the waveforms to see that peaks and troughs are co-incident, ie in-phase. If they are not, measure the phase difference and note it down.

7.2.2 Receiver/Time Varied Gain

The intention in this section is to briefly mention the important factors which must be correctly set if the signals are to remain proportional to the echoes.

Items of test equipment needed

1. Oscilloscope and calibrated probes
2. Signal generator
3. Multi-meter
4. High impedance voltmeter.

These items of equipment must themselves be in a fully calibrated condition as discussed in section 3.4.7.

NOTE A: Before making adjustment to any part of the equipment it is essential to be certain that the adjustment is absolutely necessary. Always re-check the control settings of the unit being tested, and those of the test equipment itself before carrying out an adjustment.

NOTE B: It is advisable to switch off the echo-sounding system, and to wait about 20 seconds before removing, or installing a printed circuit board (PCB). The equipment should never be switched ON whilst any board is out of its socket.

i) Receiver Bandwidth

In acoustic systems used for quantitative measurements it is important that the transmitter generates a well-shaped pulse, as square as possible, and that the receiver system has the necessary bandwidth to preserve this shape. Theoretically, if a perfect square-wave is transmitted and its shape is to be preserved in the receiver, the bandwidth of the receiver must be infinite, because a square-wave is composed of a fundamental frequency and an infinite number of harmonics. In practise, a relatively limited bandwidth will reproduce a good approximation to a square-wave. This is fortunate because the wider the bandwidth, the more noise enters the system.

To preserve a reasonable pulse shape and amplitude the minimum bandwidth BW is

$$BW = 2\tau^{-1}$$

For a 1 ms duration pulse, the minimum bandwidth is

$$BW = 2/1 \times 10^{-3} = 2000 \text{ Hz, or 2 kHz.}$$

In practice the bandwidth is not always matched to the pulse duration and Table 6 shows the compromise made with the 38 kHz and 120 kHz EK systems.

Table 6

Frequency kHz	Pulse duration τ (ms)	Actual BW kHz	kHz BW for $1/\tau$	$2/\tau$
38	0.3	3.0	3.33	6.66
	0.6	"	1.66	3.33
	1.0	1.0	1.00	2.00
	3.0	"	0.33	0.66
120	0.1	9.4	10.00	20.00
	0.3		3.33	6.66
	0.6	3.8	1.66	3.33
	1.0		1.00	2.00

The figures given in the 'Actual Bandwidth' column are those to which the system was designed and no attempt should be made to change to the figures in the columns 'Matched Bandwidth'. Despite being labelled 'Actual Bandwidth', the figures given in this column are nominal, and, whilst every effort should be made to keep to them, in practise some variation will occur. The average of 'Actual Bandwidth' figures measured from a number of echo-sounders at 38 and 120 kHz are shown below.

Table 7

Frequency kHz	Nominal Bandwidth (kHz)		Measured Bandwidth (kHz)	
	NARROW	WIDE	NARROW	WIDE
38	1.00	3.00	0.985	2.93
120	3.00	10.00	3.82	9.32

Bandwidth should never be altered unless the centre frequency has shifted, or it is evident that the shape of the bandwidth response is badly distorted. A description of a typical checking and alignment procedure follows.

With a signal generator (SG) connected to the input or TEST SIGNAL socket and a voltmeter, or oscilloscope to CALIBRATED OUTPUT, the bandwidth can be checked. The signal input level should be sufficiently great to prevent 'ragged' (noisy) edges on the CW or pulse output, but not so great as to overload the receiver at the selected GAIN position.

With the bandwidth control set to NARROW take the following steps:

Step 1 Tune the SG through the nominal centre frequency and back again, noting the frequency of maximum response (f_0)

Step 2 Reduce the frequency of the SG until the echo-sounder output level has dropped by 3 dB, ie 0.707 of the maximum, note this frequency (f_1)

Step 3 Increase the SG frequency through the position of maximum response, until the output is again -3 dB relative to maximum then call the frequency at which this occurs (f_2)

Step 4 The bandwidth is f_2-f_1

Step 5 The centre frequency is $(f_1+f_2)/2$, which should be the same as f_0

Step 6 With the bandwidth control set to WIDE

Step 7 Repeat the steps 1 to 5, but note that there are two frequencies with maximum amplitude of response now, neither of these correspond to f_0. The procedure in this case is to find the peak on the lowest side of the nominal frequency, then reduce frequency until the response is -3 dB relative to maximum, call this f_{w1}

Step 8 Increase frequency through the first peak, on to the second and continue until the response is -3 dB relative to the second peak (highest frequency). Call this f_{w2}

Step 9 The WIDE bandwidth and centre frequency can be calculated in a similar manner to 4 and 5 above.

ii) Pre-amplifier GAIN control check

Take the following steps:

Step 1 Connect the test instruments as shown in the manufacturers handbook

Step 2 Set the echo-sounder controls as below

TVG and GAIN	0 dB (any of the two 0 dB positions)
TEST/OPERATE	TEST
BANDWIDTH/PULSE DURATON	NARROW: note that the bandwidth selector of the EK is marked NARROW and WIDE, whereas the EK-R and EK-S are marked with the nominal andwidth. Any of the 3 positions of NARROW bandwidth can be used.

EK-S models

(a) Basic range selector 0

(b) Disconnect tx trigger cable at recorder main terminal.

Step 3 Switch on the echo-sounder

Step 4 Adjust the SG to the nominal working frequency of the echo-sounder

Step 5 Set the function selector of the test set to Rec. The voltmeter will now measure the calibrated output of the echo-sounder

Step 6 Adjust the attenuator and/or level control of the SG until the voltmeter reads 0 dB (1 V_{rms})

Step 7 Set function selector of the test set to Gen. The voltmeter will now show the output from the generator (input to 'test signal')

Step 8 Read the voltmeter and then calculate the gain

$$G = A - V_{in} + VR$$

where G = voltage gain in dB

A = attenuation in the echo-sounder (dB)

V_{in} = level of input signal to test signal point

VR = level of signal at calibrated output dB/V

The nominal gain of the pre-amplifier is 85 ± 0.5 dB

NOTE: the trimmer control R 35 or R734 (depending on the echo-sounder), is for adjustment of pre-amplifier gain.

Step 9 Set the function selector of the test set to Rec., the voltmeter should read 0 dB. If the reading differs more than 0.2 dB from this repeat steps 4-8

Step 10 Change the 'TVG and GAIN' control to one of the positions -20 dB, the voltage reading should drop by approximately -20 dB. If the reading falls from 0 dB to 19.7 dB the gain of the pre-amplifier is reduced by 19.7 dB when the TVG and GAIN is set to -20 dB. Note the measured value of the attenuator

Step 11 Set TVG and GAIN back to one of the 0 dB positions and the voltmeter deflection should be 0 dB. If this is not so repeat steps 4, 5, 6, 10

Step 12 Change the bandwidth selector to one of the four positions giving WIDE bandwidth. The difference in reading should be very small when changing between NARROW and WIDE. Note the difference if any, if more than 0.5 dB check the complete bandwidth characteristic of the receiver

Step 13 Repeat the steps 4, 5, 6, with selector in WIDE position. Then repeat step 10 and 11. Note reduction in gain for -20 dB position of TVG and GAIN control. It should be about equal to the result for NARROW bandwidth.

NOTE: Allow time for the equipment to warm-up before making any measurements (about 10 minutes).

7.2.3 Time Varied Gain Amplifier Calibration

The echo-sounder and echo-integrator can be calibrated utilizing standard targets or measurements on live fish. These calibrations are valid at the depth of the experiment if the TVG function of the echo-sounder is known to be correct at that depth. But it is also necessary to ensure that the calibration is valid for the whole depth range covered by the TVG. The manufacturer specifies the accuracy of the TVG function to be within ±1 dB of the appropriate law but, even so, this can result in an intensity difference of 2 dB between the shallow water, where the standard target or the live fish calibration experiment was carried out and the depth where fish concentrations are found during survey. As 2 dB corresponds to a factor of 1.58 this could lead to a large error in the estimate of a fish stock. It is necessary to keep errors to the minimum possible, but

although it is desirable to have a TVG function with a maximum deviation of less than 0.5 dB (± 0.25 dB) this is not practical with equipment prior to 1980.

The EK equipment is designed to have an accuracy of ± 1 dB, so it is necessary to measure the TVG function and introduce a correction in the acoustic estimates according to the difference between the theoretical TVG function and that actually measured. Several methods of measurement may be utilised, depending upon the equipment available. All use the gain of the TVG amplifier (pre-amplifier) at a certain depth for reference and compare this with the gain at other depths.

i) TVG Calibration Method ONE

This TVG measurement utilises a Continuous Wave (CW) signal generator, an electronic counter, AC voltmeter and oscilloscope. Take the following steps:

Step 1 Connect test the instruments as shown in Figure 56.

Step 2 Prepare a table similar to table 5 by calculating the theoretical values for $20 \log R + 2\alpha R$ or $40 \log R + 2\alpha R$ at suitable range increments. Remember that the value of α is dependent on temperature and salinity.

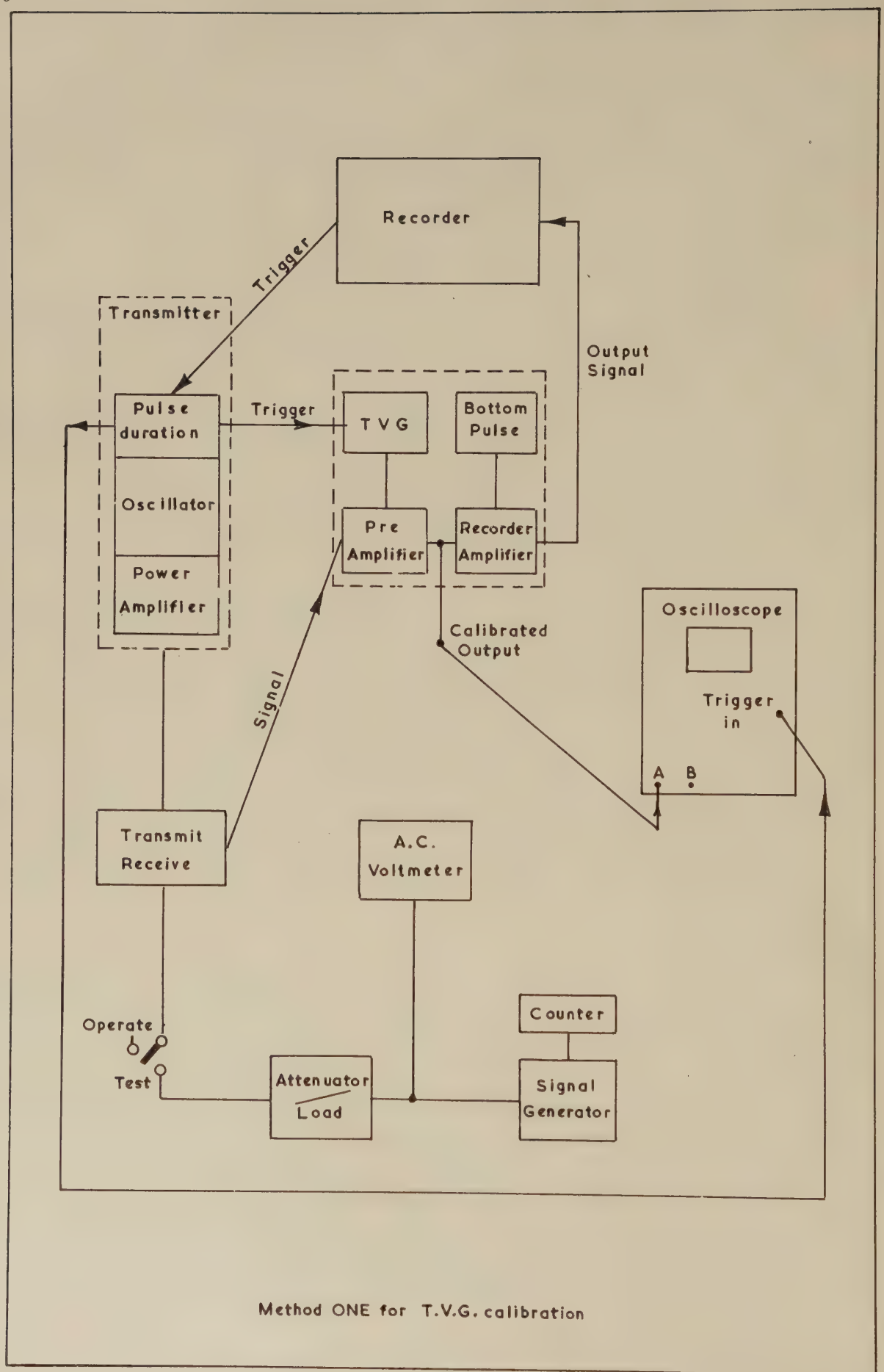
Step 3 Adjust the frequency of the signal generator to the centre operating frequency of the echo-sounder, and its amplitude to the reference signal level (say -40 dB/V).

If the noise level permits, a lower reference level ie -60 dB/V may be used. The lower the input, the less chance there is of over-heating the receiver input stage during the gain measurement, this helps to preserve the accuracy at short ranges. Theoretical values have been calculated for both -40 dB/V (A) and -60 dB/V (B) reference levels.

Step 4 Select the TVG function to be measured (20 logR or 40 logR).

Step 5 Adjust the polarity and triggering level of the oscilloscope, so that stable triggering is obtained from the positive leading edge of the transmitter trigger pulse. Make sure that the timebase of the oscilloscope will cover a sufficient range.

Figure 56



Method ONE for T.V.G. calibration

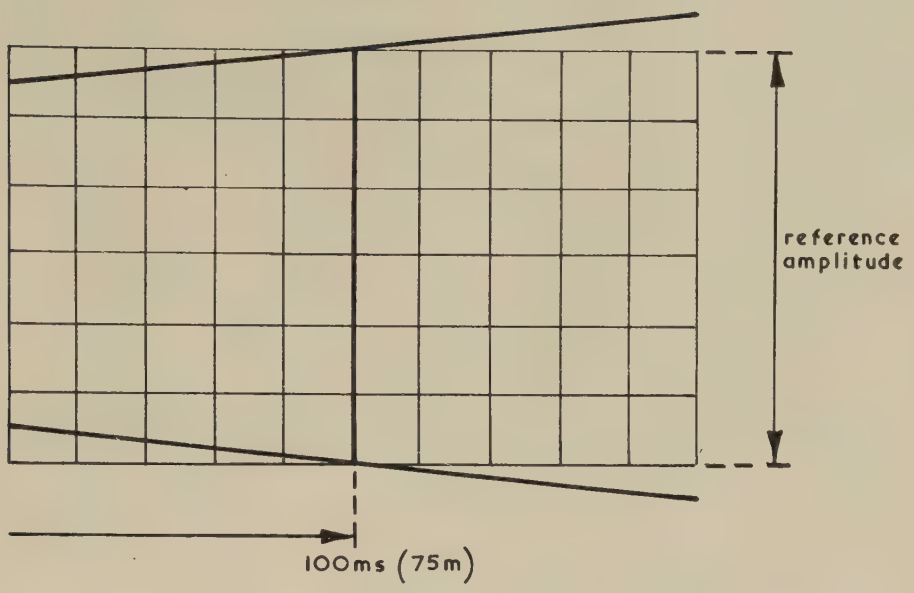


Figure 57

Step 6 Adjust the oscilloscope vertical sensitivity until the picture at the reference depth eg 75 m (100 ms) from the start, exactly fills the screen between the two main horizontal division lines (one at the top, one at the bottom of the screen) Figure 57. The vertical sensitivity of the oscilloscope should be left untouched during the rest of the measurements.

Step 7 Now alter the level of the signal generator output until the reference amplitude is obtained at one of the other ranges given in the table. Read off the signal level and note down the result in the table.
Note: To make it easier to read the voltmeter, stop the recorder of the echo-sounder while the voltmeter readings are taken.

Step 8 Repeat step 7 until all points in the table have been measured. Try to spend the minimum time possible at short ranges. The CW signal output of the generator is high, and the transistors may heat up slightly, thus causing a change in their characteristics and upsetting the measurements.

Example 1:

We are measuring the 20 logR + 2αR function of a 120 kHz echo-sounder. A reference level of -40 dB/V is selected, and the oscilloscope adjusted to give reference amplitude at 100 ms.

The output level from the signal generator is then reduced until the reference amplitude is presented at the oscilloscope screen at 133 ms. Stop the echo-sounder recorder and read the output level of the signal generator on the voltmeter. Write down the result eg (-44.9 dB) in the table. Start the recorder and increase the signal level until reference amplitude is obtained at 60 ms. The signal generator output level is again measured and the result put into the table. Then repeating the same procedure for all points in the table we have the following result. Note: for simplicity, α has been ignored in this example.

Table 8

Range		Theoretical dB		Measured value dB		Difference dB
metres	ms	A	B	A	B	A
3	4.0	- 5.4	-25.4	- 4.5		+ 0.9
4.5	6.0	- 9.1	-29.1	- 2.3		+ 0.8
7.5	10.0	-13.8	-33.8	-13.2		+ 0.6
15.0	20.0	-20.5	-40.5	-20.3		+ 0.2
37.5	50.0	-30.5	-50.5	-31.0		- 0.5
45.0	60.0	-32.8	-57.8	-32.9		- 0.1
75.0	100.0	-40.0	-60	-40.0		0
100	133	-44.8		-44.9		- 0.1

The difference is calculated as:

Difference = measured value - theoretical value.

Step 9 The difference between the measured value and theoretical value is now plotted in the graph, Figure 58 and this graph can then be used to correct the calibration constant to ensure that it is valid for the depth where the major fish concentrations are registered.

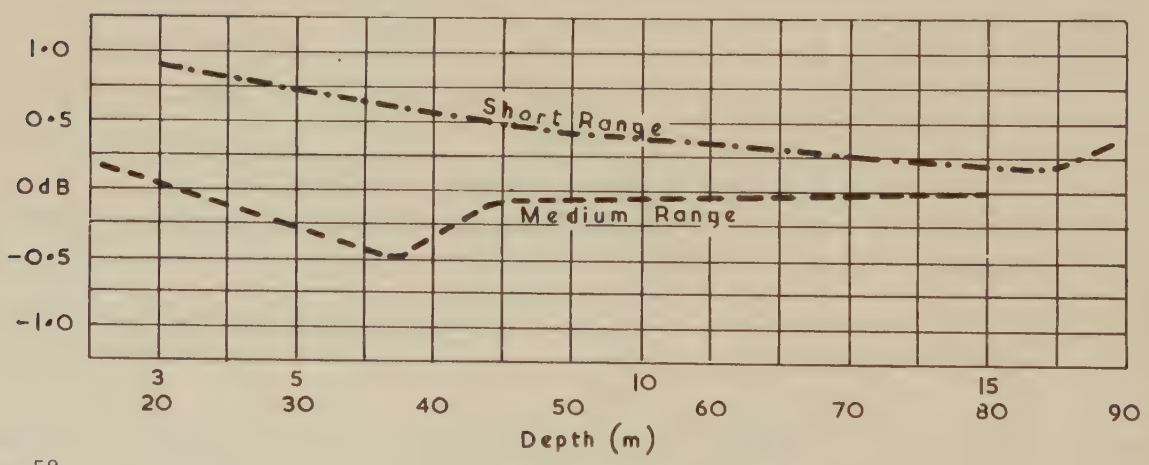
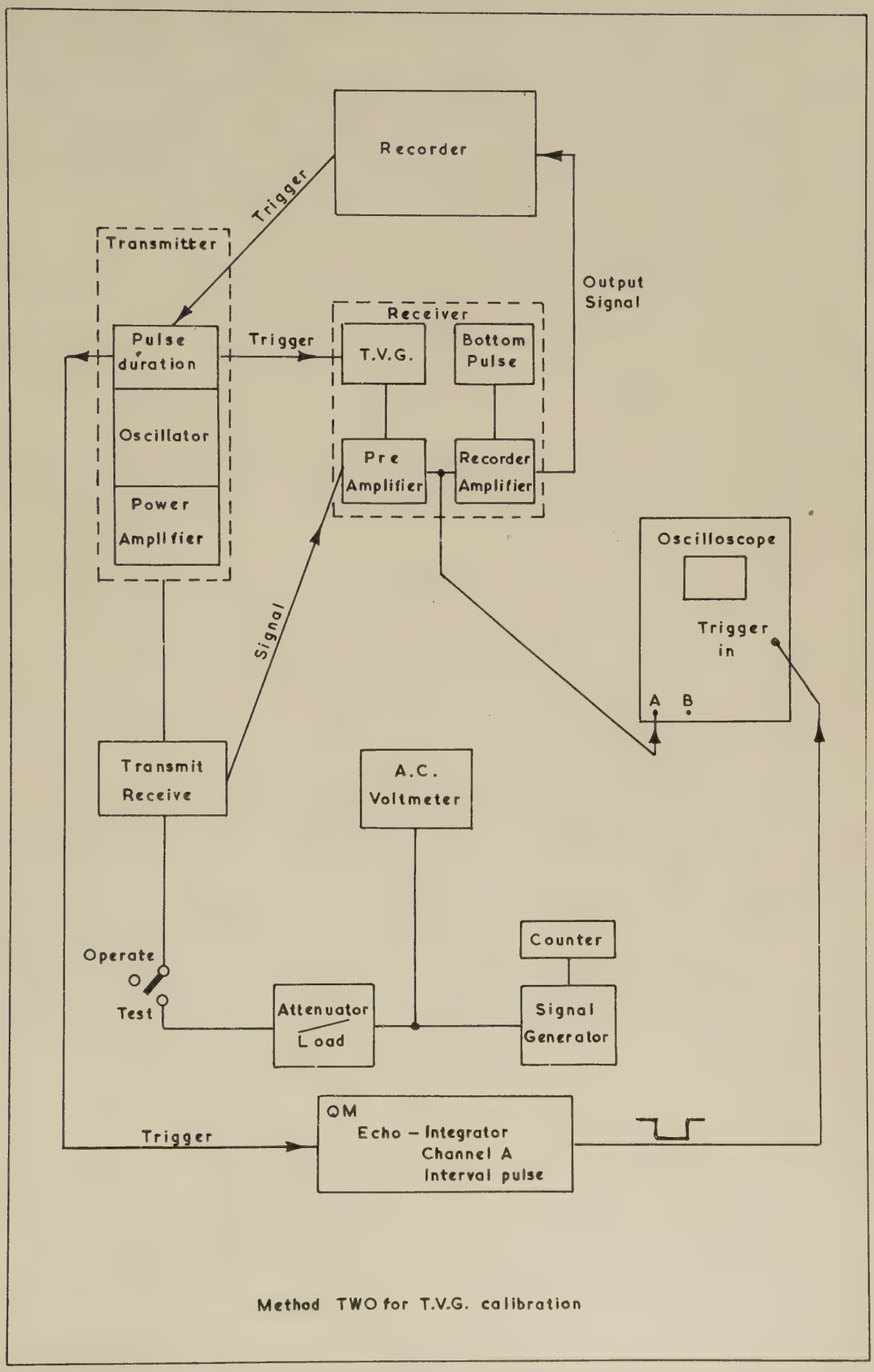


Figure 58 TVG Deviation Graph

Example 2:

Using the 120 kHz echo-sounder from the previous example, we have made a live fish calibration. Distance from the transducer face to the centre of the integration interval was 4 metres during the calibration. When using the same equipment at sea for an abundance survey, heavy fish concentrations at between 50 and 60 metres depth are found in one area. We want to find the correct calibration constant to convert the echo-integrator deflection 'M' corresponding to these fish concentrations to absolute values.

Figure 59



Method TWO for T.V.G. calibration

Solution: From the graph we find that the 'error' of the TVG at the depth of the calibration (4 m) hence our reference is +0.83 dB. On survey the fish are found at a depth of between 50 and 60 m. The average depth of the fish, (55 m) corresponds on the graph to a TVG 'error' of -0.03 dB so the total difference is therefore (-0.03) + (-0.83) dB = -0.86 dB. Consequently, the constant 'C' must be reduced by 0.86 dB, or be divided by 1.22. The same result is obtained if the calibration constant kept at its original value but the integrator deflections are divided by 1.22

ii) TVG Calibration Method TWO

Again measuring the TVG function using a CW signal generator, an electronic counter, an A.C. voltmeter, an oscilloscope and an echo-integrator. This method is similar to that just described, the difference lies in the use of the interval pulse from the echo-integrator, to trigger the oscilloscope, so only a small part of the total TVG function is presented on the screen. The procedure is:

Step 1 Connect the instruments as shown in Figure 59.

Step 2 Adjust frequency of signal generator to the centre operating frequency of the echo-sounder and its amplitude level to the reference given in the manufacturers table.

Step 3 Start the echo-sounder and display the interval pulse from the echo-integrator on an oscilloscope. Adjust triggering level of the oscilloscope so that it occurs at the leading edge of the interval pulse.

Step 4 Select a 2 m interval and adjust the timebase of the oscilloscope so that the interval corresponds to the total width of the screen (10 divisions). The leading edge of the interval pulse corresponds to the depth selected and the trailing edge to this depth plus two metres, the centre of the screen corresponds to the selected depth plus one metre.

Step 5 Now display the signal from the calibrated output. Set the depth selector of the echo-integrator to one metre less than the reference depth, and the latter is then displayed at the centre of the screen.

Step 6 Adjust the vertical sensitivity of the oscilloscope until the centre of the displayed picture covers the whole screen, minus one division above and below the curve (Figure 60). Do not alter the oscilloscope controls after it has been calibrated as described above.

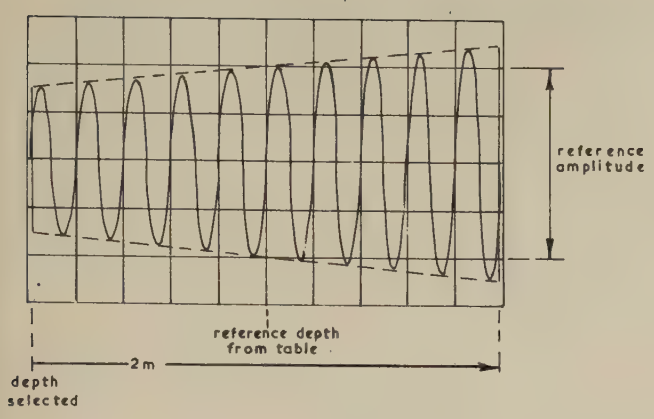


Figure 60

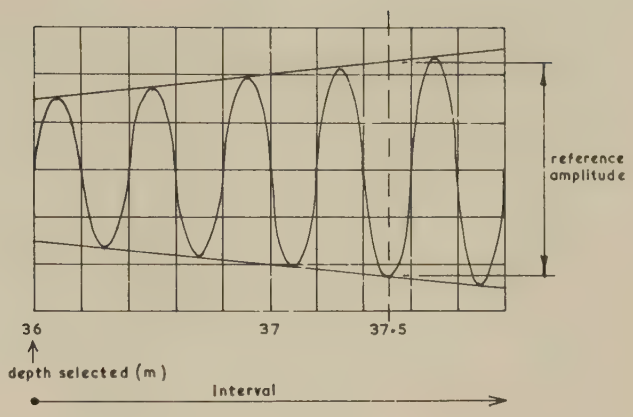


Figure 61

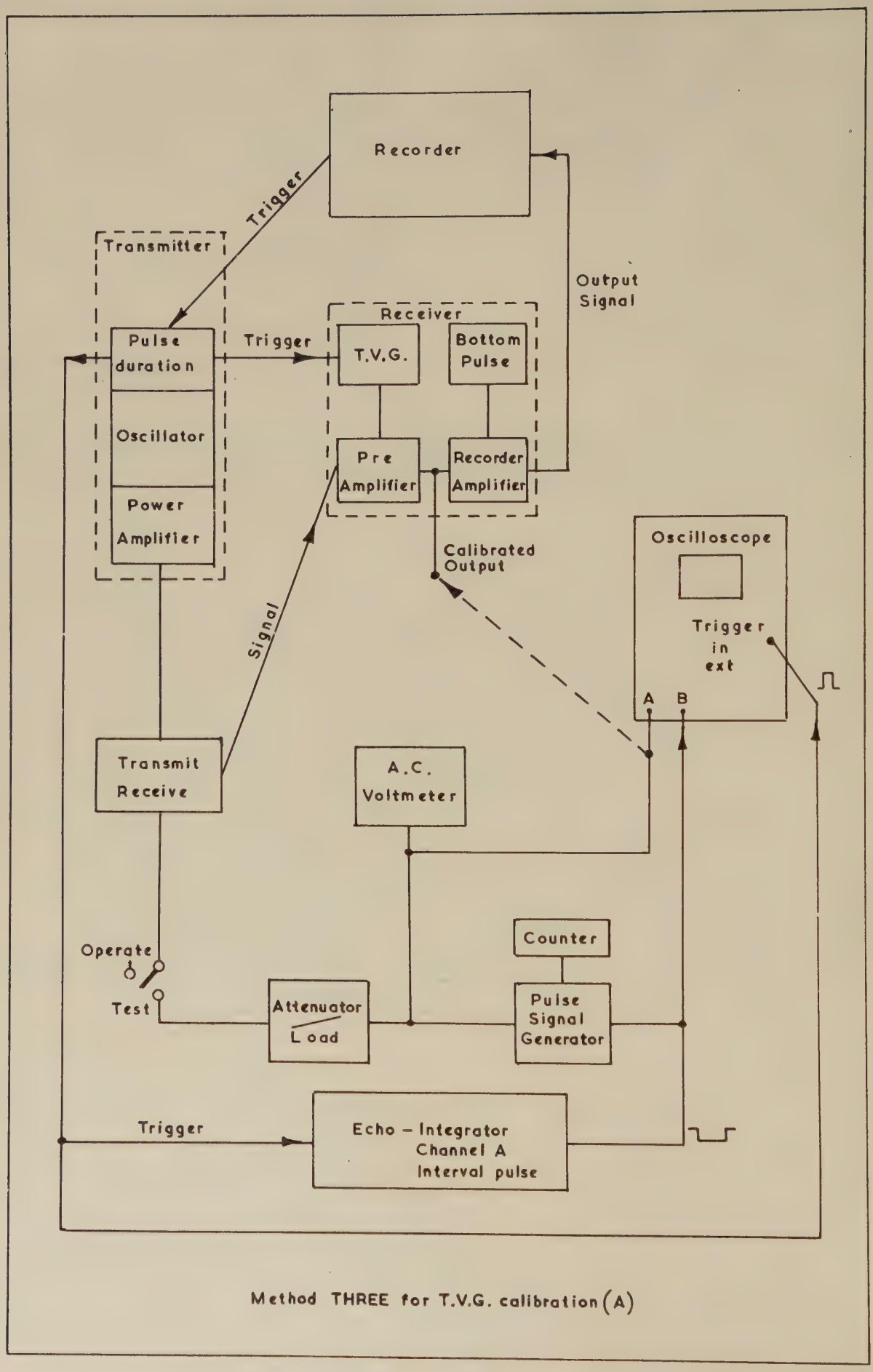
Step 7 The rest of the procedure is similar to that described in method ONE. From the table, another point on the curve is selected and the depth control of the echo-integrator is set to 1 metre less than the depth found in the table.

Output from the signal generator is adjusted until the reference amplitude is obtained at the centre of the oscilloscope screen, the recorder of the echo-sounder is then stopped and the signal level read from the AC voltmeter. These results are written down in the table. Some of the measurements in the table refer to half metres (for example 37.5 metres). In this case set the depth selector of the echo-integrator to a depth of 1.5 metres less than the depth found in the table (for example 36 m). This depth is now found midway between the centre and the right hand side of the screen. (For a screen with 10 divisions, at division 7.5). In this case adjust the level of the signal generator until reference amplitude is found at this position of the screen, Figure 61.

Step 8 Proceed with the measurements in similar manner as described for method ONE.

Calculate the difference between the measured and the theoretical value and plot the error curve.

Figure 62



Method THREE for T.V.G. calibration (A)

iii) TVG Calibration Method THREE

Measurement of the TVG function using a pulsed signal generator, electronic counter, A.C. voltmeter and an oscilloscope.

This method is similar to the previous two. The difference is that the continuous wave (CW) signal generator, is replaced by one which may be triggered or amplitude modulated in such a way that a signal pulse or burst is produced. This avoids heating up of the amplifying transistors due to continuous high signal input. The TVG amplifier is therefore checked under normal operating conditions and a more exact result expected.

Step 1 Connect the instruments as shown in Figure 62.

Step 2 Start echo-sounder and switch on the echo-integrator.

Step 3 Select CW mode of operation for the signal generator and adjust its frequency to coincide with the echo-sounder operating frequency and its output level to 0 dB.

Step 4 Adjust oscilloscope triggering level (external) and polarity (+) until a stable triggering occurs. Use dual beam mode, and select sweep speed and vertical sensitivity so that the signal generator output and the echo-integrator interval pulse are both clearly visible, as shown in Figure 63.

Figure 63

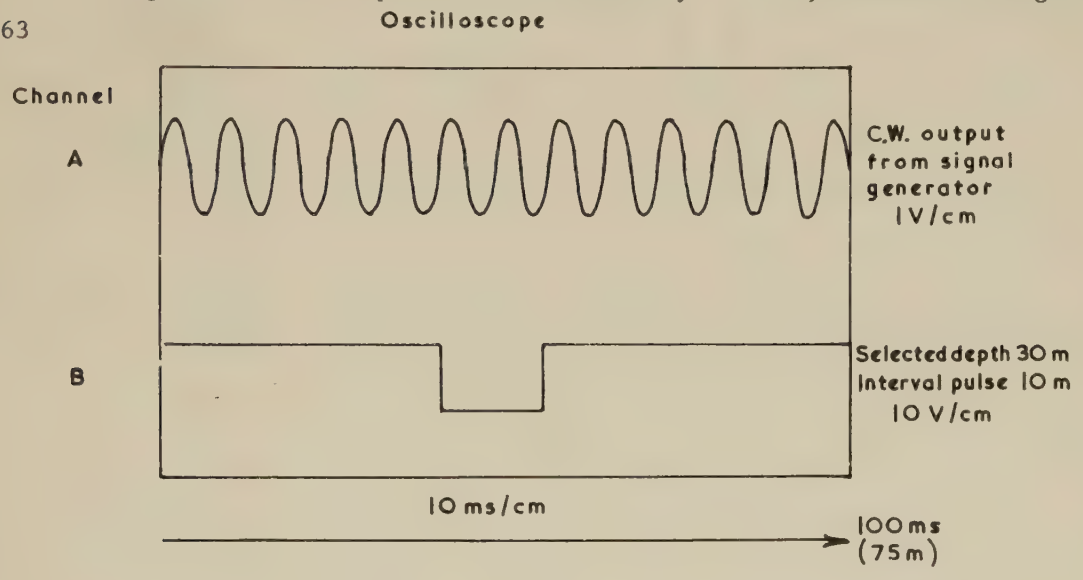


Figure 64

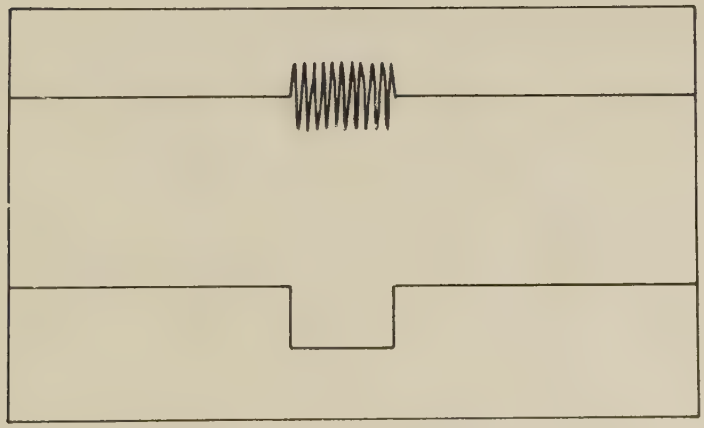
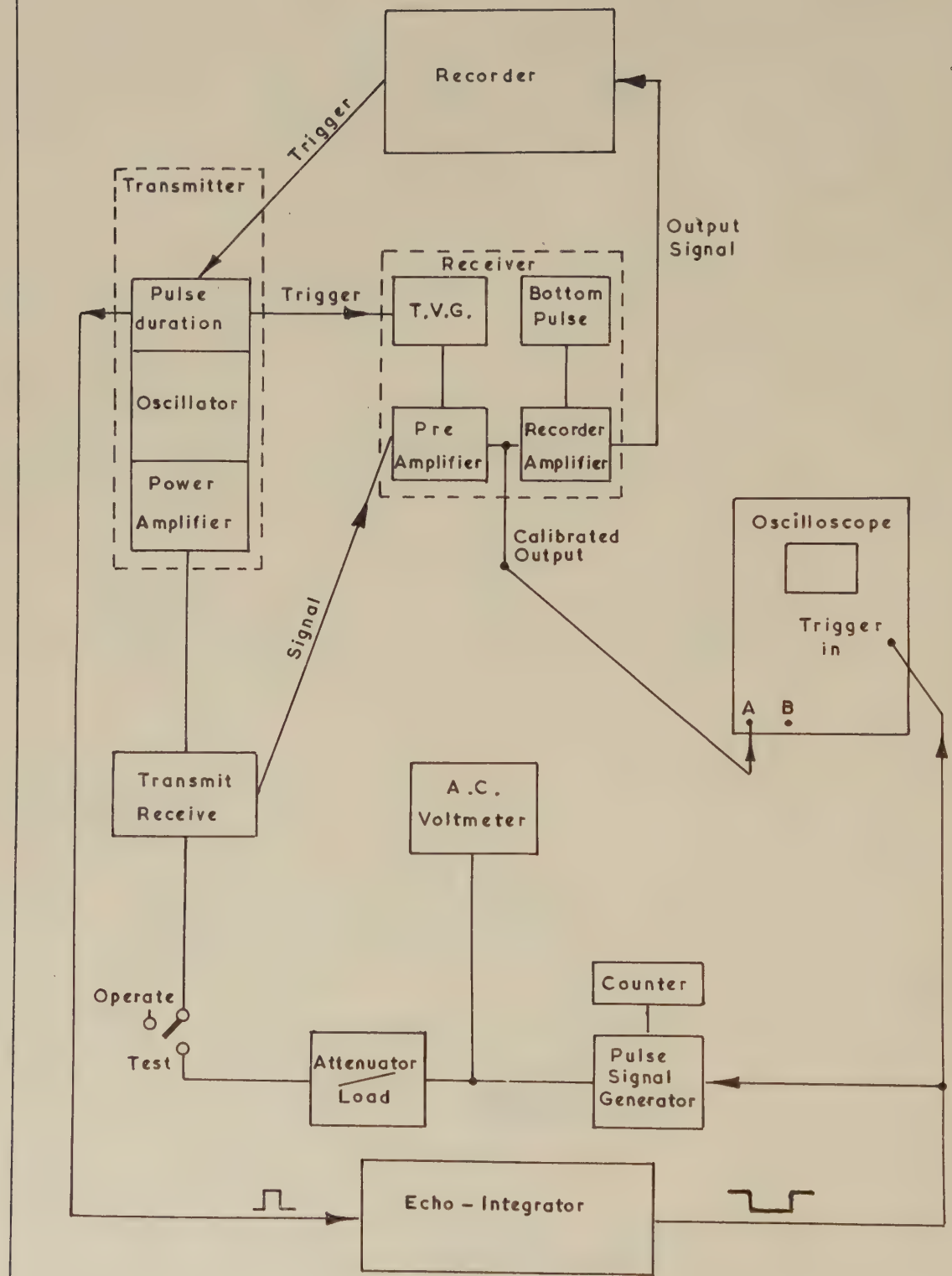


Figure 65



Method THREE for T.V.G. calibration (B)

Step 5 Select triggered mode and external gate control at signal generator, then adjust triggering level and polarity (-) until the generator produces a stable signal pulse, Figure 64.

Step 6 Now connect the oscilloscope channel A vertical input, to the echo-sounder calibrated output. The pulse signal should appear on the screen, although its amplitude will be much higher and the signal generator output level should be reduced until the whole pulse is within the screen. The instrument connections should now be as shown in Figure 65.

Step 7 Select the Channel A only mode on the oscilloscope and adjust vertical position of the pulse until it is centred on the screen.

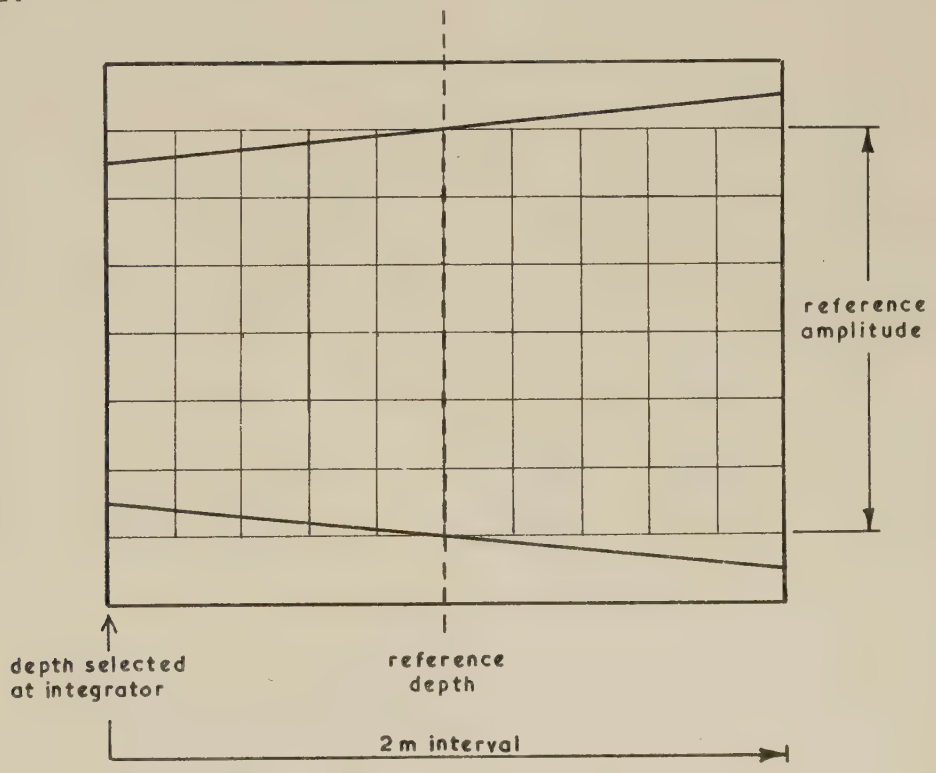
Step 8 Stop recorder (without switching off the echo-sounder).

Step 9 Set signal generator mode selector to CW. Check that the generator frequency is still equal to echo-sounder operating frequency. Correct if necessary. Adjust output level of generator to reference level.

Step 10 Start recorder of echo-sounder. Select triggered mode of signal generator. Set depth selector of the echo-integrator to one metre less than the reference depth and the interval selector of the same channel to 2 m.

Step 11 Trigger the oscilloscope from the Channel A interval pulse of the echo-integrator.

Figure 66



Step 12 Adjust vertical sensitivity and sweep speed of the oscilloscope until a picture similar to the one shown in Figure 66 is obtained. Do not alter the oscilloscope settings after they have been adjusted in this way.

Step 13 Change the depth selector on the echo-integrator to a position one metre* less than the depth indicated for one of the other measuring points in the table. Adjust the generator output level until reference amplitude is obtained at the centre of the oscilloscope screen, stop the recorder, change generator mode to CW and read off the level on voltmeter. Go back to triggered mode, start echo-sounder recorder and repeat this step until enough points on the TVG curve have been measured. Note down the results in the table. Continue as described in method ONE from step 9 and beyond. (*If the depth to a measurement point is now a half metre, eg 37.5 m, select one and a half metre less than in the table and adjust the output level of the signal generator until reference amplitude is obtained on the oscilloscope screen, midway between the centre of the pulse and its end).

NOTE: Other methods of TVG calibration have been developed since the material given in 7.2.3 was prepared by B. H. Larsen but these require specialised instruments. One such was reported by Lee (1982) and Foote (pers. comm.) stated that H. P. Knudsen of the Institute of Marine Research in Bergen has designed and built the necessary circuits for automated measurements. Automated calibration is also mentioned by Hood and Huggins (1983).

7.2.4 Integrator

Correct functioning of echo-integrators can be checked by various methods involving the application of pulse or continuous wave signals at the input terminals and monitoring the output by digital voltmeter or chart recorder (Simrad QM). Actual setting up of the analog circuits is a difficult and lengthy procedure but a quick overall system check for the QM echo-integrator is as follows

Set the controls to

Depth	012 metres	Threshold	Zero
Interval	030 "	Bottom Stop	OFF
Gain	10 dB	Operate/test	test
		Speed (Manual)	10 knots

Monitor the following

Signal	3.16 positive pulse
Interval	+15V to 0V, duration 40 ms, delay 9 ms
Sounding	3.64V positive pulse, approx 100 ms
Nautical mile	0.32V steps rising to 10V and resetting.

The nautical mile output takes 31 trigger pulses to reach 10V. Look at the record on the QM recorder and count the steps.

The Simrad QD system has a built in test panel which allows a number of functions to be monitored but of course they are of a different type to the analog systems. In this case for example the signal from the echo-sounder is in the form of a 12-bit word. The pre-integrated squared signal can be checked to least significant and most significant bits and the status of all the controls bits can be observed by means of LED lights.

8. ORGANISATION OF WORK AND PROCEDURES

8.1 Importance of Team Work

Effective team work is important for the successful conduct of acoustic surveys. Such surveys may be carried out at different levels of complexity and their objectives may range from a purely academic nature to the fishery resources surveys dealt with in this manual.

Common to the whole range of surveys is their multi-disciplinary nature, a fact that necessitates cooperation and collaboration between personnel from different disciplines. Fisheries acoustic surveys are usually carried out by a team of biologists, oceanographers, electronics engineers, fisheries engineers and fishing gear technologists, ie essentially a group of scientists and engineers. Each person shares the general watchkeeping duties, but must be ready to apply his individual skills at any time for the benefit of the team as a whole. Members of the team must ensure continuity of survey records, with strict regard to their annotation including a full description of unusual occurrences.

Experience in FAO Projects has shown that the biologist can profit from the skills of the engineer, and the engineer needs the knowledge supplied by the fishery biologist. In this connection Scientists and Engineers consider themselves to be professional in a very broad sense, as shown by the following quotation from Brown (1962).

> "A profession is man-centred in two ways: (1) it demands practitioners who are free and responsible individuals and who, through their personal integrity, dedication, and courage, can be depended upon to establish and maintain their personal standards of performance; (2) a profession, no matter how technical the procedures it employs, demands that its practitioners be primarily motivated by service to their fellow men.
>
> A learned profession is a still more demanding occupation. Two further ingredients are required: (1) a learned profession requires years of preparation of the whole man and of his knowledge and skills; (2) it also requires the learning approach throughout life, as a means of fulfilling one's responsibility to one's fellow men, through the ready application of new knowledge."

8.2 Planning and Design of Surveys

8.2.1 Objectives and Background Information

"The ultimate aim of most resource surveys is to provide facts and information to potential investors who are interested in developing a new fishery or extending an existing fishery, Mackett (1973). Therefore, the working objectives of the survey must be consistent with the information needed to make wise investment decisions". Also, the monitoring of fish stocks and their scientific management have become increasingly important in recent years. In these contexts, the working objectives of acoustic surveys may be diverse, although in essence they are focussed on fish distribution and abundance.

The individual surveys may be carried out with widely varying objectives depending on their location, timing, the nature of the resource, and also on the specific questions asked. To illustrate this, the following examples from published work are given:

1. To establish indices of 0-group fish, e.g. in the Barents Sea (Haug and Nakken, 1977).
2. To estimate abundance of a spawning stock, e.g. Blue whiting in the area West of the British Isles (Buzeta and Nakken, 1975), or the Icelandic Capelin stock (Vilhjálmsson and Reynisson, 1979).
3. To assess the spatial distribution and abundance of a sardine stock, e.g. in the Northern Adriatic Sea (Burczynski and Azzali, 1977).
4. To determine apparent distribution and estimate total biomass in large lakes, e.g. Lake Tanganyika (Johannesson, 1975) or Lake Titicaca, Peru (Johannesson, et al, 1981).

These examples reflect the differences one can find in the objectives of typical real-life surveys. Moreover, a single survey often has the secondary objective of studying diurnal variations in fish behaviour and their general distribution pattern.

In the case of survey programmes operated over a period of many years, the objectives generally are for stock monitoring which may place varying emphasis on; changes in seasonal distribution pattern and abundance, migratory behaviour, composition of recruit and other stock components (year-classes), and provide a direct measure of the impact made by an active fishery on adult stock, e.g. in the course of a fishing season. Examples of the operations and objectives of actual systematic surveys can be found from different countries such as, India (Bazigos et al. 1980), Norway (Midttun, 1979), and Peru (Johannesson and Vilchez, 1979).

Another important aspect of the 'objectives' is that once they have been established, certain bounds can be put on the survey exercise in terms of methods and means (e.g. manpower, vessel time, fishing gear, etc) required to accomplish these objectives. Consequently, the development of objectives should be regarded as a prerequisite to the process of planning an acoustic survey.

Contrary to academic research, where the hypothesis holds a central place in the formulation of ideas concerning the 'little-known' system being worked on, and where the

research effort is directed towards the testing of that hypothesis, the objectives of an acoustic survey generally imply that we are mostly dealing with 'known' systems. Take a typical survey objective - "To determine the distribution and absolute abundance of stock X in area Y". Logical examination tells us that before we can estimate the size of the stock X it is imperative to have a priori knowledge of its likely distribution. Also, the objective implies that we already knew that the area Y was inhabited by the stock X, i.e. that certain information about the biology and the environment of the area was available prior to the establishment of the working objectives of the survey. The important point here is a close relationship between a realistic survey objective and the existing scientific and historical knowledge of the system. Any rational survey planning must take this into account if a survey exercise is to yield the desired results.

8.2.2 Operational Aspects

The exact execution of a given survey grid is governed by two factors: the statistical and the operational. This section deals with the latter and 8.2.3 with the statistical considerations. One criterion for a well-designed survey is that the survey transect pattern should be operationally suitable. For example, a vessel working in an area where steady winds are blowing (monsoon), may sail relatively smoothly (minimum roll and pitch) on a given course, whereas sailing on a different course line would result in much movement of the ship and cause a consequent noise increase. Thus, the first course would be suitable in the circumstances, but not the latter.

In the design of the grid pattern, due attention should be paid to the operational capacity of the vessel, the quality of its navigational aids and the general safety arrangements. With respect to the last factor it must be borne in mind that many pelagic fish stocks exhibit almost littoral distribution characteristics which often require that the survey vessel continues running the inshore transect in to a depth of 10 m, or even closer to the shore. Obviously in such a situation, a vessel carrying a powerful skiff, fitted with side-thrusters and powerful anchors, would take much less risk operating in shallow waters, than another vessel without such facilities. In addition to these technical considerations, experience has amply demonstrated that the efficiency with which inshore waters can be acoustically sampled depends largely on the competence and co-operation shown by the officer in command of the survey vessel. Hence, good co-operation and collaboration between a captain and a survey cruise leader can be of crucial importance to the efficient conduct of the survey.

Usually, acoustic surveys are carried out either in the form of parallel or oblique (zig-zag), grid patterns. Figure 67 shows the principle design of such patterns for the particular case when there are an equal number of transects per unit area. In the following we will examine the differences between the two transect patterns, with particular reference to factors such as: vessel time, vessel speed, area coverage and transect spacing.

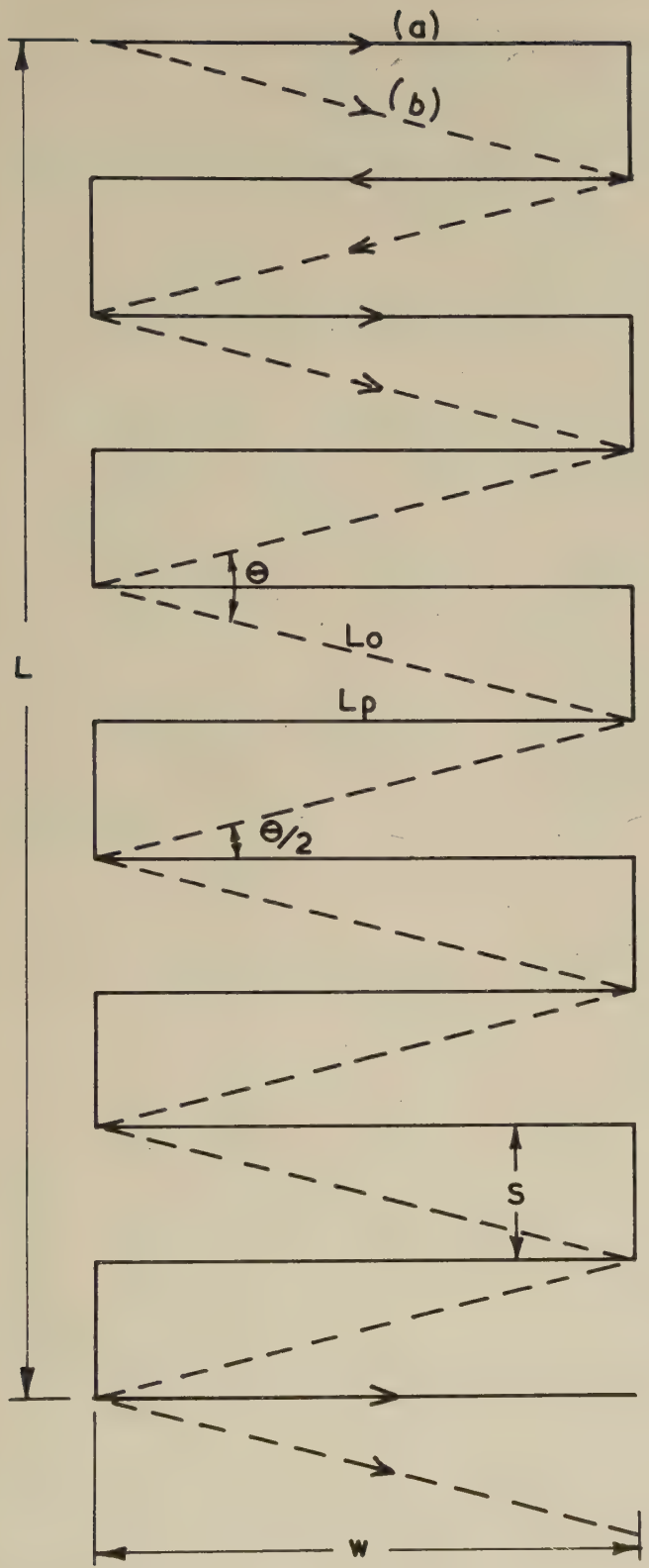


Figure 67 Parallel vs. oblique transect pattern

Np = Number of parallel Transects

No = Number of oblique Transects

(Np = No)

Lp = Length of parallel Transects (nautical miles)

Lo = Length of oblique Transects (nautical miles)

w = width of survey area (w = Lp)

$\Theta/2$ = oblique - grid half-angle (degrees)

L = Length of survey area (nautical miles)

d = duration of survey (days)

V = vessel speed (knots)

t_e = effective sailing time (hrs/day)

S = Transect spacing (nautical miles)

(a) Parallel survey grid

(b) Zig-zag survey grid covering approximately the same area with same number of transects

Parallel grid

By a combination of simple algebraic and geometric considerations, one can derive the following formulae for the parallel grid.

$$V \times t_e \times d = N_p \times L_p + (N_p - 1) \times S = K$$

where: V = vessel speed (knots)

t_e = actual sailing time at speed V (hours/day)

d = duration of survey (days)

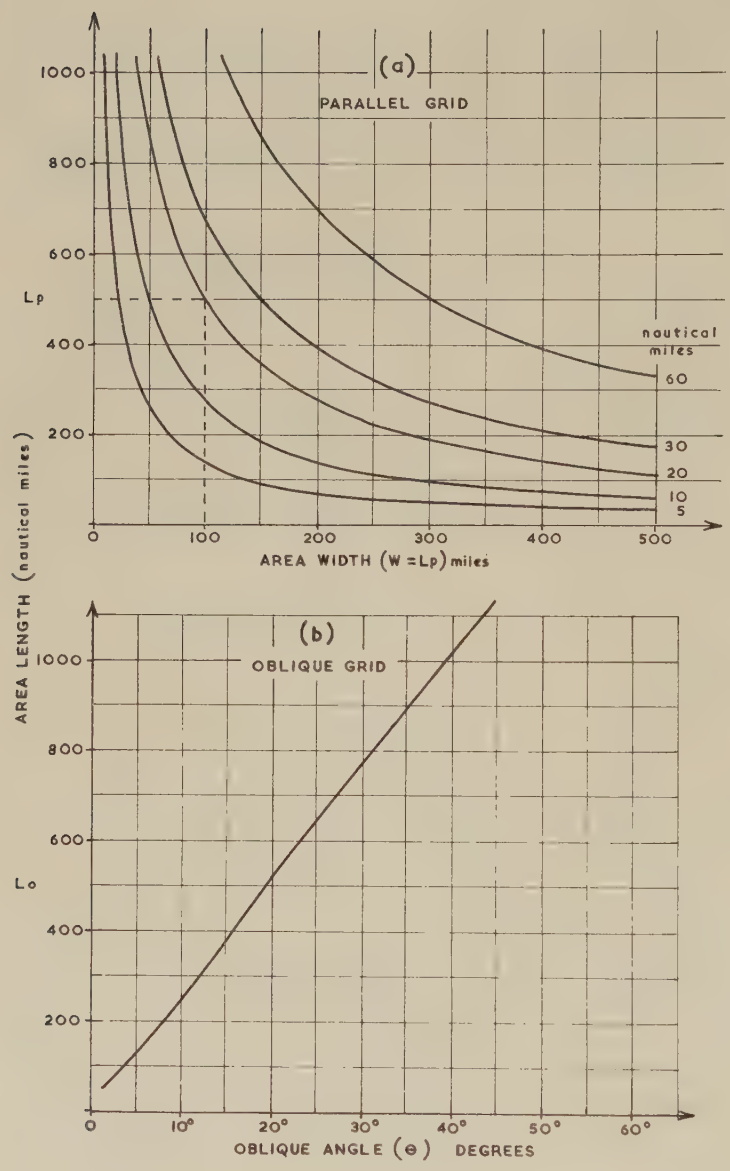
N_p = number of parallel transects

L = length of rectangular survey area (nautical miles)

S = equidistant transect spacing (nautical miles)

L_p = length of the parallel transect (nautical miles), (= W, area width)

Figure 68



Assuming that: $(N_p - 1) \simeq N_p$

we can write

$$N_p \times L_p + N_p \times S = K$$

and that $N_p S \simeq L$

then substituting

$N_p \simeq L/S$ we obtain

$$K = L\,(1 + Lp/S)$$

On examination, we observe that the quantity K is a constant for steady vessel speed, sailing time per day and duration of the survey.

Example: V = 10 knots

t_e = 20 hours/day

d = 15 days

Then K = 10 x 20 x 15 = 3000 (total vessel track, nautical miles). Using the typical values above and solving the equation for L, we obtain

$$L = 3000\ S/(S + L_p) \text{ nautical miles}$$

The above equation is useful for planning purposes because, for a given total survey track and selection of equidistant transect spacing (S) as parameter, it gives the relationship between the rectangular area, length versus width, and hence the corresponding area coverage. Figure 68(a) presents a graphical solution of this equation for: S = 5, 10, 20, 30 and 60 nautical miles.

Oblique (zig-zag) Grid

To examine the different operational characteristics of the parallel versus the oblique transect pattern, it is convenient as a first step to distinguish between two situations as follows:

First situation: The assumption is made that both transect types span over an equal area-width and that the number of transects per unit area is the same. (In this connection it should be recognized that the distance S (Figure 67) does not refer to a transect but is commonly referred to as 'connecting leg' or 'inter-transect leg'). Based on these assumptions and a qualitative examination of the geometry of the situation, it will be realized that the operational differences are: (a) The oblique grid coverage requires shorter total survey track and hence vessel time, and (b) with increased obliqueness (measured by the angle Θ), the ratio in total track length between the parallel track (T_p) and the oblique track (T_o) will increase. Mathematically this ratio can be established as follows:

$$T_p/T_o = (W + S)/L_o \qquad \ldots\ldots\ldots\ldots (76)$$

and as $\cos \Theta/2 = (W/L_o)$, we may write

$$T_p/T_o = ((W + S)/W)\text{Cos } \Theta/2$$

Example 1: S = 20, W = 100

Then: $\text{Tan}^{-1}\ \Theta/2 = \text{Tan}^{-1}\ (20/100) = 11.31°$

and: $T_p/T_o = ((100 + 20)/100)\text{Cos } 11.31° = 1.177$

Example 2: S = 20, W = 20

Then: $\text{Tan}^{-1}\ \Theta/2 = \text{Tan}^{-1}\ (20/20) = 45°$

and: $T_p/T_o = ((20 + 20)/20)\text{Cos } 45° = 1.414$

In practice it is rather unlikely that the angle Θ will assume values higher than 45° so, as a rough guide, one may consider about 40% as the maximum time saving offered by the zig-zag survey grid, given the above assumptions.

Second Situation: Here the assumption is made that an unknown size of survey area is covered by the same total track length, i.e. $T_o = T_p$; or alternatively, that both track types cover the same width, but not the same length (rectangular area).

In this case the angle Θ is dependent on the parallel transect spacing and could theoretically take any value from 0° - 180°. However, as in the previous situation it is

not likely to exceed values of about 90°, i.e. $\Theta/2 = 45°$. Based on the above, one can establish the following equations.

I. Total track length:

a. $T_p = NpW + NpS = Np\ (W + S)$

b. $T_o = No \frac{W}{\text{Cos } \Theta/2}$

and as we have specified that $T_p = T_o$, it follows that $Np\ (W + S) = N_o\ (W/\text{Cos } \Theta/2)$

II. Area length consideration:

a. $L_p = Np \times S \rightarrow Np = L_p/S$

b. $L_o = NoW \tan \Theta/2 \rightarrow N_o = L_o/W \tan \Theta/2$

Substituting N_p and N_o in the previous equation related to track lengths, we obtain

$$L_p\ ((W/S) + 1) = L_o/\text{Sin } \Theta/2$$

and finally:

$$L_o/L_p = ((W/S) + 1) \text{ Sin } \Theta/2$$

To illustrate the meaning of the above equation we first consider the graphs in Figure 68(a) and note that $L_p = 500$ for $S = 20$ and $W = 100$, corresponding to an angle $\tan^{-1}(20/100) = 11.31°$. Inserting the same values in the above equation we obtain

$$L_o = 500\ (\frac{100}{20} + 1) \times \text{Sin } 11.31° = \underline{588.4}$$

and $L_o/L_p = 588.4/500 = 1.177$

which shows that for the given angle, and when both survey grids have equal total track length, and span the same area width, the zig-zag transect pattern will cover an area approximately 18% larger. Using the same values for L_p, S and W, but a variable angle $\Theta/2$ (i.e $T_o = 3000 \times \text{Sin } \Theta/2$), illustrates more clearly the relationship between the angular width of an oblique track and the resulting length or area coverage. The results covering an angular range from $\Theta = 1°$ to $\Theta = 45°$ are shown in Figure 68(b).

8.2.3 Survey Design

The task of selecting, or developing an appropriate grid design for an acoustic survey, requires that a number of criteria be satisfied both in regard to distribution information and sampling theory. At the outset it is useful not only to be cognizant of the survey objectives and operational aspects, but also to consider other important factors. A reliable independent acoustic estimate of stock size over a large area can be achieved with echo-sounder/integrator methodology provided that the following general conditions are satisfied.

(a) The fish stock is known to be available for acoustic measurement in the survey area.

(b) The stock is relatively homogeneous over the survey area.

(c) The stock is not inextricably mixed with other stocks or fish populations in the area.

(d) Fish are neither too deep, nor too shallow to be effectively detected.

(e) Distribution of the fish over the area is sufficiently constant for valid extrapolations to be made from density measurements along widely-spaced survey transects.

(f) The fish are not disturbed by the vessel (avoidance effect) before measurement by the acoustic system.

For many stocks, these conditions are reasonably well satisfied; for others they are not. Clearly one must distinguish between demersal fish stocks and pelagic stocks; between pelagic stocks found in the northern hemisphere and those existing in tropical waters; between relatively stationary, pelagic stocks found in localized areas and those which are highly mobile and found in offshore waters; between relatively small, dispersed stocks (low-productivity areas) and those that are large and characterized by a high degree of school activity and often 'patchiness' (high-productivity areas). Also, the designer of the survey must taken into due account the characteristics of the survey environment itself.

The design of an acoustic survey aimed at providing absolute estimation of the size of a fish stock must be based on a thorough knowledge of the biology, distribution and behaviour of the fish. If such information is not at hand, a series of pilot surveys, covering extensive areas and different seasons may be necessary before an efficient quantitative survey can be reasonably well designed.

Assuming that the required background information is available, the survey design process can begin to focus on the type of course track to be established. As defined by Shotton (1979) "The cruise track designs must be such that the estimate is unbiased and it should permit an evaluation of both the precision of different designs, or modifications of the same design as well as an objective evaluation of the precision of the sampling result".

It is at this stage that the theory and concepts of statistical sampling need to be drawn upon to aid in the design problem. For the present purpose it is convenient to discuss the principles and requirements for a statistical design, a process involving concepts such as: population (the fish stock), the sample (integrator survey values) and randomization (ie the selection of the sample, referring to the mode, or pattern, by which the allocation of samples was made during the survey).

Randomization is the cornerstone underlying the use of statistical methods in survey design and, ideally, it is used to prevent systematic sampling errors. By randomization we mean that the distribution of the fish comprising the population and the order in which the separate transects, or sample observations, of the survey are to be performed are both random. Some statistical methods require that the observations be independently distributed random variables. By properly randomizing the survey, we will assist in 'averaging out' the effects of extraneous factors that may be present. Having stressed the importance of randomisation, it should be pointed out that in terms of probability, the random sampling procedure means that, if the population contains N elements, each has a specified and usually equal probability of being sampled.

In section 9.1.0 we define and explain the systematic and random errors and draw attention to the fact that random errors will govern the precision of a stock estimate. We also indicate that a statistical parameter 'standard error' could be used to provide an estimate of the level of precision. Again, referring to Shotton (1979), "a survey track should be designed so as to permit objective evaluation of the precision of the sampling result". Some elaboration of this statement is desirable. First, it is important to be aware that when data from an integrator survey are treated as statistical sample units, each observed integrator reading (y) is conceived as an individual sample mean with its own underlying statistic (e.g. $\bar{y}$) and the entire set of data as a sampling distribution of means. In such a case the sample mean is

$$\bar{y}_s = \sum^{n} \bar{y}_i / n \qquad \ldots\ldots\ldots\ldots (77)$$

where n is the number of integrator readings in the sample,
the variance is then given by:

$$\text{Var } (\bar{y}_s) = S^2/n$$

and the standard error of the mean $\text{S.E. } (\bar{y}_s) = S/n^{\frac{1}{2}}$

where S is the standard deviation computed from

$$S = \sum_{i=1}^{i=n} (y_i - \bar{y})_n^2 \; / \; (n - 1) \qquad \ldots\ldots\ldots\ldots (78)$$

The precise definition and the method of calculation of this is described in textbooks on statistical methods, for example in that of Goulden (1952). However, a good idea of its meaning can be grasped by considering that in about one case out of three the estimate will be in error by more than ± the standard error, and in one case out of twenty the estimate will be in error by more than ± twice the standard error.

Accepting these statements for our present purpose, it should be made clear that the standard error can theoretically be subjected to a problem regarding accuracy. When an estimate is suspected to have bias for which a correction cannot be made, then the mean square error (MSE) should be used to measure the error rather than the variance. The MSE includes components due to variation of the sample estimate about its expected value $E(\bar{y})$ and the difference between the expected value of the sample estimate and the parametric mean, i.e. bias. The important property of the mean square error can generally be shown as follows:
Let one population parameter such as the mean μ be estimated by the sample mean $\bar{y}$. If this is a biased estimator so that

$E(\bar{y}) = \mu + \Delta$ where Δ is the bias, either a positive or a negative quantity then by definition

$$\begin{aligned}
\text{Var}(\bar{y}) &= E[\bar{y} - (\mu + \Delta)]^2 \\
&= E[\bar{y}2 - 2\bar{y}(\mu + \Delta) + (\mu + \Delta)^2] \\
&= E[\bar{y}2 - 2\bar{y}\mu - 2\bar{y}\Delta + \mu^2 + 2\mu\Delta + \Delta^2] \\
\text{rearranging terms} &= E[\bar{y}2 - 2\bar{y}\mu + \mu^2 + \Delta^2 + 2\Delta(\mu - \bar{y})] \\
&= E[\bar{y} - \mu)^2 + \Delta^2 + 2\Delta(\mu - \bar{y})]
\end{aligned}$$

Since $E(\mu - \bar{y}) = -\Delta$

$$\text{Var}(\bar{y}) = E[(\bar{y} - \mu)^2] - \Delta^2$$
$$E[(\bar{y} - \mu)] = \text{Var}(\bar{y}) + \Delta^2$$

or in other words:

$$\text{MSE} = (\text{variance of } \bar{y}) + (\text{bias})^2$$

demonstrating that the variance of the estimated sample mean $\bar{y}$ is an underestimate of the true variance around the population mean μ. The value of the standard error, and hence the precision of any particular survey, will depend on

(a) the intrinsic variability of the fish population under study

(b) the number of sample units, e.g. integrator observations or the number of survey transects

(c) the design of the survey (and on the method of analysis if this is not fully efficient).

Considering the above factors, it will be realized that while we cannot control (a), we can increase the precision of the survey estimate by increasing the survey effort and where conditions allow, by adopting probabilistic survey design that would also be aimed at reducing bias in the sampling. After having briefly discussed the theoretical principles of a statistical survey design we may ask how well these procedures work out in practice. In fact, few designs currently used in acoustic fish stock abundance surveys satisfy the criteria of elementary sampling theory.

The main reason for this, apart from the fact that statistical sampling theories were not originally developed for the purpose of describing and quantifying aquatic fish populations, is probably that whilst truly statistical designs seem more feasible for demersal surveys, most applications of acoustic methods to date have concerned pelagic surveys, i.e. fish populations whose distribution pattern is often highly dynamic with respect to time and space and for which it is more difficult to define naturally occurring sampling units, or strata. In the latter type of survey there is a tendency to assume that a systematic survey grid pattern with non-randomly selected starting point, e.g. of the type shown in Figure 69 would serve as a valid approach because the fish themselves, by their general mobility about the fixed survey tracks, would take care of

the theoretical 'randomization' requirement. Although the validity of such an assumption cannot be realistically made, this is no reason why a systematic survey should not start in a pre-determined geographic position. For further study of this particular problem the interested reader is advised to consult well known textbooks on statistical sampling, e.g. Cochran (1963) and also papers of Shotton (1981), Bazigos (1981) and Shotton and Bazigos (1982).

After having reviewed the principal requirements for achieving successful and statistically efficient survey grid designs, we will now briefly examine some distinct survey designs and discuss their differences both in relation to their strategic and statistical characteristics. These are selected from published work on actual surveys and cover the following principal cases: (i) Large pelagic stock in an open sea area, (ii) Large pelagic stock exhibiting almost littoral distribution pattern, (iii) Medium-size, highly migratory pelagic stock, (iv) Small and relatively stationary stock, and (v) Demersal fish stock.

i) Large Pelagic Stock in an open sea area

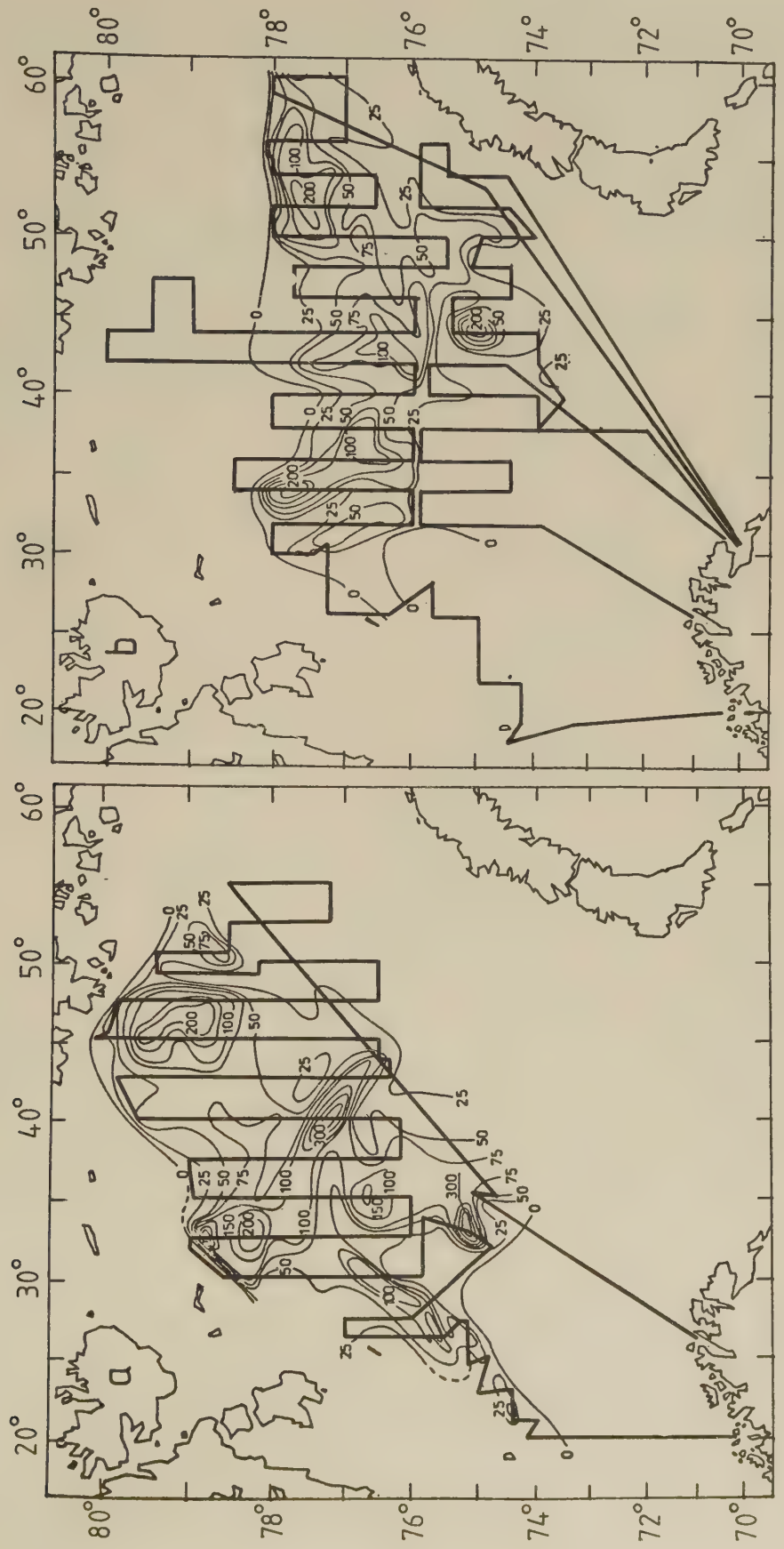
A good example is presented in Midttun and Nakken (1977) and relates to the Barent Sea capelin stock. Figure 69, (a) and (b) shows a typical survey grid design based on parallel course lines with approximately equidistant spacing of 40 nautical miles. The present design does not allow for 'randomness' or proportional allocation of survey effort and, therefore, falls in the category of purposive surveys (Shotton, 1981). Emphasis is placed on maximum coverage, i.e. the vast geographic extent of stock distribution pattern ($\sim$ 120,000 mile^2) can be covered adequately within the time available and other operational constraints.

This is particularly important for a stock-oriented survey which aims at estimating the total stock biomass and year-class strengths, as opposed to given area or region-oriented surveys. Prior to the survey, the most probable area of stock distribution is predicted in the light of information from past surveys, and fishing activities. The transects are generally run across the entire width of the distribution using either a pre-specified low, or zero, integrator value as the criterion for determining their north-south limits. For a large-scale survey of the type described, it is of crucial importance that the fish distribution over the area is sufficiently even for valid extrapolations and interpolations to be made from density measurements along the relatively widely-spaced survey transects.

ii) Large Pelagic Stock Exhibiting Littoral Distribution

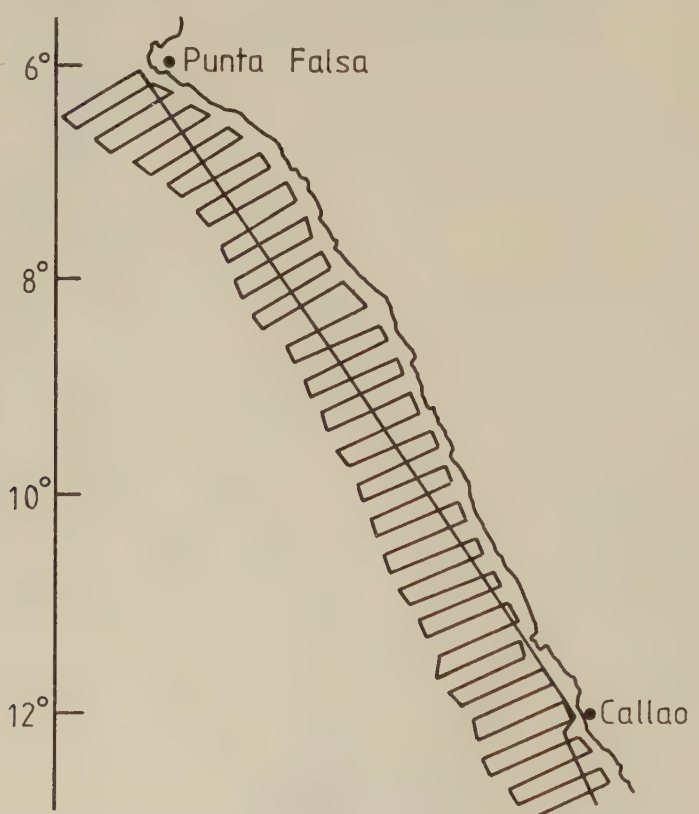
The Peruvian anchovy is a good example of the above situation, as detailed in Johannesson and Vilchez (1979). Figure 70 illustrates the type of survey grid pattern that was used as a standard over a period of many years when the stock level was 5-10 million tonnes. The parallel transect design was preferred, rather than the zig-zag

Figure 69 Survey grid for Barents Sea capelin stock. Parallel courses with 40 nautical mile spacing (Midttun and Nakken, 1977)



design, largely because of ease in navigation and also because the selected course lines happened to minimize vessel movements (roll and pitching) against the prevailing wind directions. As in the previous example (i), no attempt is made to apply any form of random design but much emphasis is placed on dense coverage with transect interspacing kept to only 10 miles. Because the anchovy stock generally exhibit contagious distributions (as illustrated by the fact that for certain surveys less than 2 percent of the surface area could contain about 20 percent of the total estimated biomass), a relatively dense survey grid is required to obtain a representative sample, especially within the high-concentration areas. The size of the individual transects is determined by the inshore limit (often 15 m depth), depending on navigational safety, and the seaward limit, which can vary considerably from survey-to-survey. Consequently, the general strategy is to observe closely the level of integrator readings along the seaward transect run (these could vary in the range from 5-5000 mm), and after traversing the main concentrations with the readings getting lower and finally reaching zero-levels, the transect is discontinued and the vessel proceeds to work the next transect. Simultaneous evaluations of the corresponding echograms can also play a role in such semi-subjective decision making.

Figure 70



iii) Medium-size, Highly Migratory Pelagic Stock

The Icelandic capelin stock provides an almost ideal example on the problems and possibilities of making quantitative acoustic surveys of highly mobile stocks. This particular stock has been subjected to intensive acoustic surveys since 1978, Vilhjalmsson, et al (1982). The report is enlightening because it shows that the task of estimating the abundance of a pelagic stock for management purposes can present more problems of strategy and effort than of measurement. Figures 71a-d show the principal migration

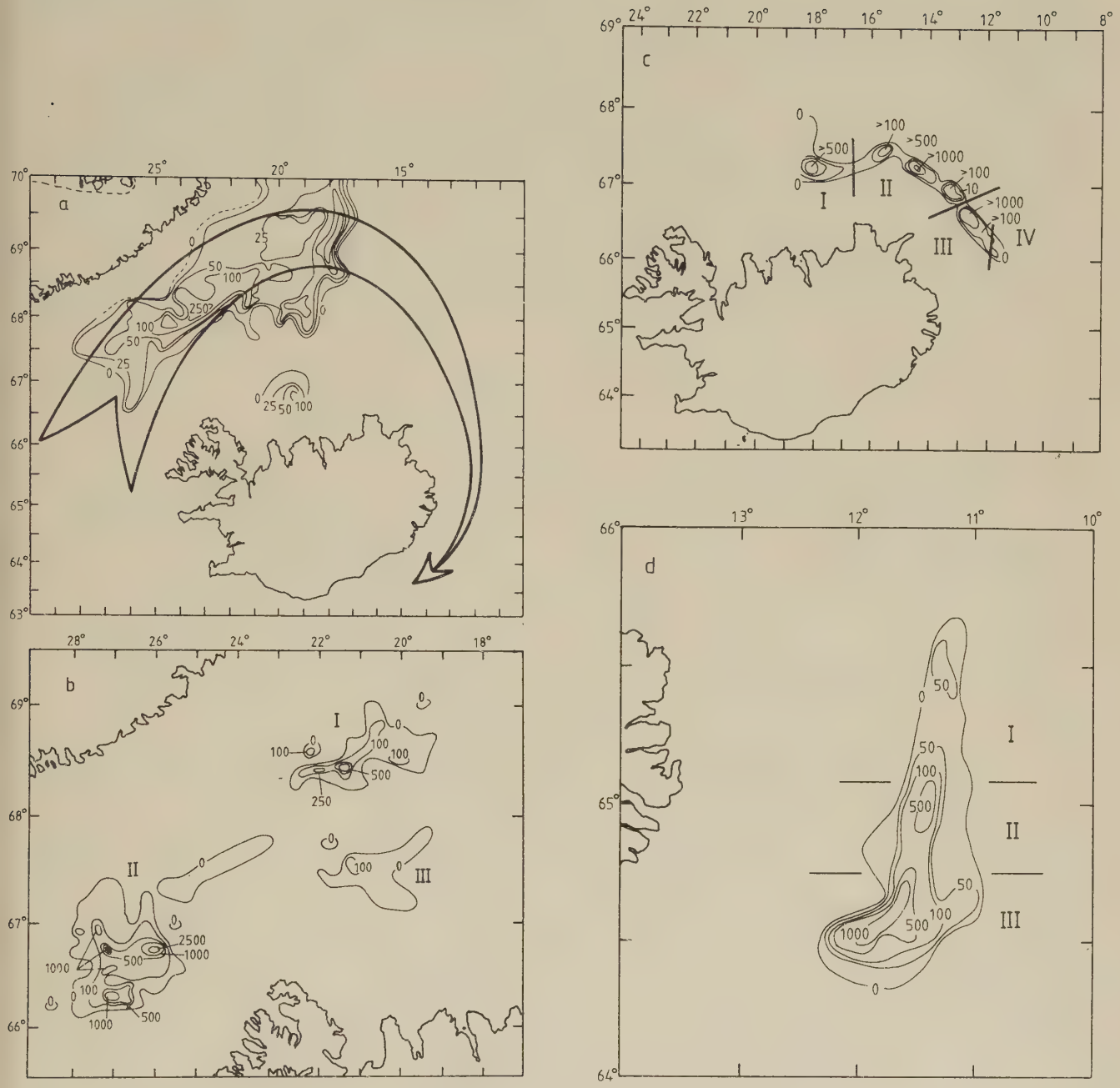


Figure 71 (a-d)

route of the capelin stock, together with several stock distribution patterns obtained from strategically timed surveys in the period from July 1979 to January 1982. Survey track-lines are not shown, but were of the common, non-random zig-zag type with varying density. Transect lengths were generally determined on the basis of 'zero' readings as explained under case (i). The strategy can be summarized as follows: During the feeding period which lasts from April to September-October, when the stock may break up into geographically separate components Figure 71b, a series of surveys is conducted to monitor the general distribution pattern and fish behaviour as well as the presence of drift ice, a factor that may influence the environmental conditions considerably. In the post-feeding period the stock gradually aggregates to form one unit again, (Figure 71), a process continually monitored by rapid surveys based on coarse track designs. Once the stock has formed a well defined geographic and depthwise distribution pattern (Figure 71d), coupled with good weather conditions, a replicate survey is conducted to obtain a reliable estimate of spawning stock size.

This example brings out an important factor when compared with the Peruvian situation because the latter is characterized by statistical implications, but the success of the Icelandic capelin surveys depends primarily on strategic execution.

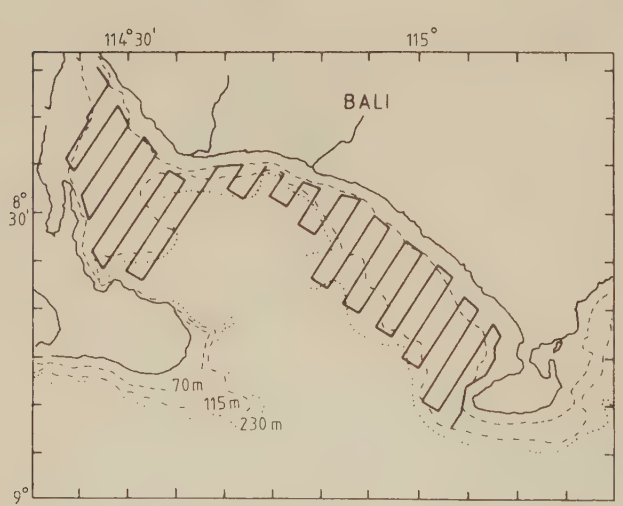
iv) Small and Relatively Stationary Pelagic Stock

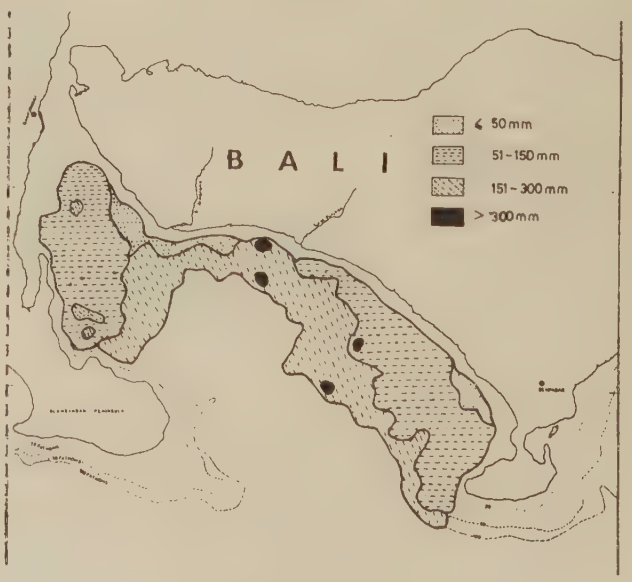
Many examples could be cited but only the local sardine stock inhabiting the Bali Strait, Indonesia, will be mentioned. Figure 72(a) shows a typical survey design and (b) distribution pattern of the stock which, according to recent estimates, has a size of 30-40,000 tonnes. Again, the transect design is of the non-random parallel type, covering the whole area of interest. As will be noted, the inter-transect spacing is only 2 miles which is considered intuitively to be adequate for statistical purposes.

Figure 72

(a) Survey grid for area near Bali

(b) Stratification of survey area into 4 density categories





The Bali Strait sardine can be considered a "stationary" stock for survey purposes so for this reason, the survey design above is maintained as a standard. Consequently, any demand to increase the precision of the survey estimates is not met by changing their statistical design. It is done by conducting replicate surveys, which, on the scale considered, are not too time consuming, or costly, and will give more realistic assessment of the absolute precision of the survey estimates.

v) Demersal Fish Stock

An interesting design for demersal surveys is presented in Shotton (1981), who discusses the evolution of survey methodology at the Bedford Institute of Oceanography, Canada. Figure 73 indicates track design for an echo survey of demersal fish on the Scotian Shelf. The cruise tracks are designed to give representative coverage of the strata comprising the shelf. Thus, there is no explicit randomization of the design or proportional allocation.

Figure 73

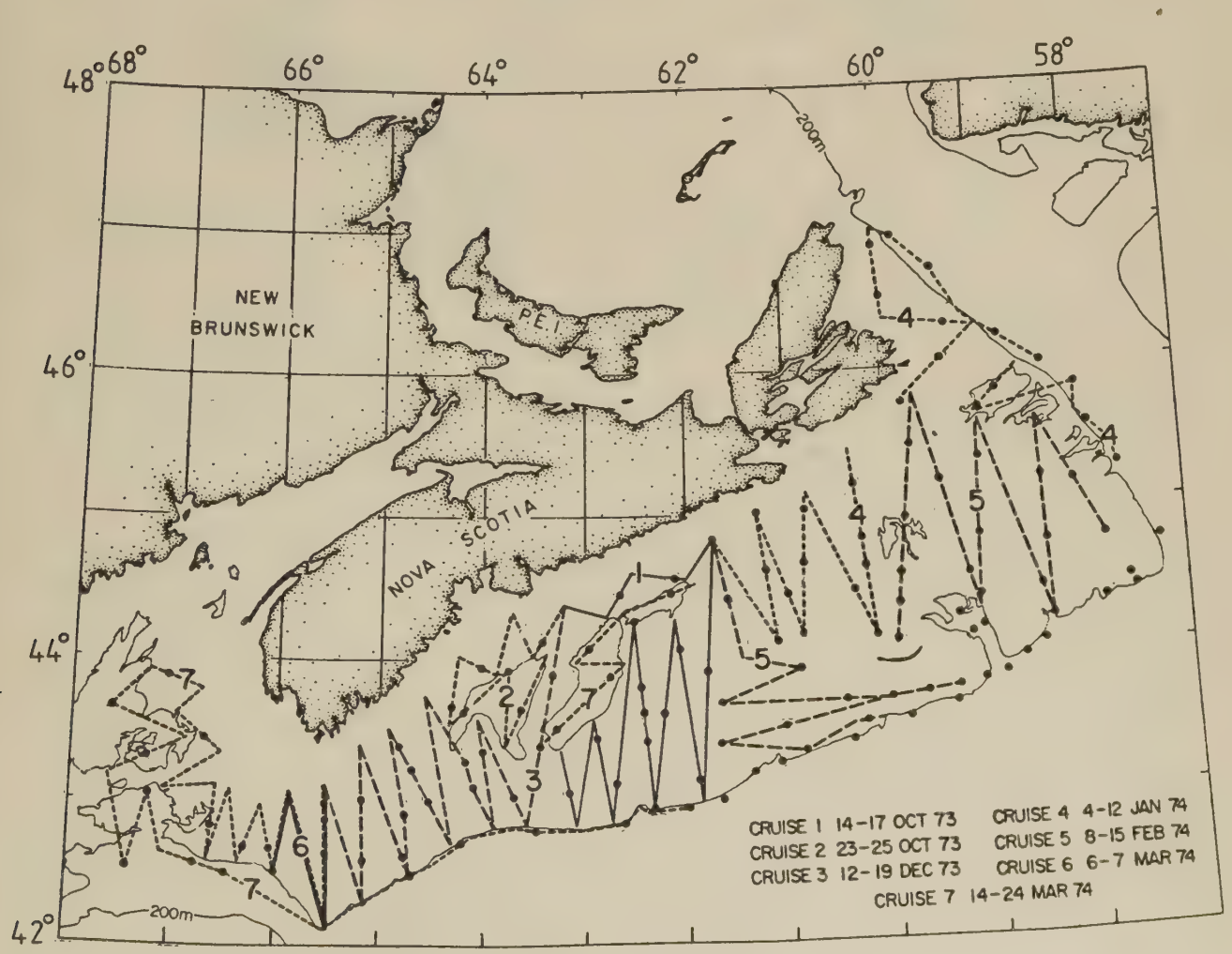
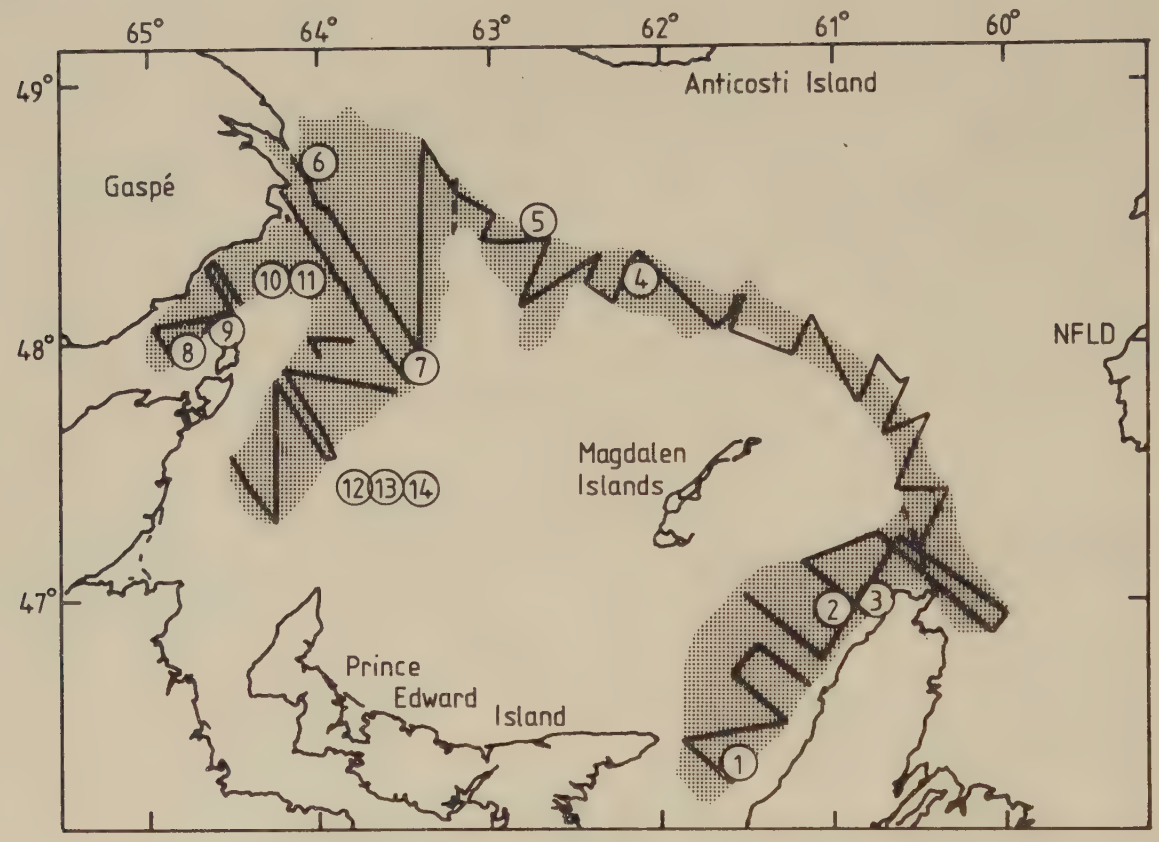


Figure 74 shows a design for an assessment of the 4T cod stock in the southern Gulf of St. Lawrence, intended to cover the expected summer range of the stock. The region is divided into blocks with one sampling transect per block located at random. Shotton (1981) writes: "If each transect is assumed to consist of a single sample, an estimate of the sample variance may be obtained by grouping the strata in pairs. Slight

Figure 74

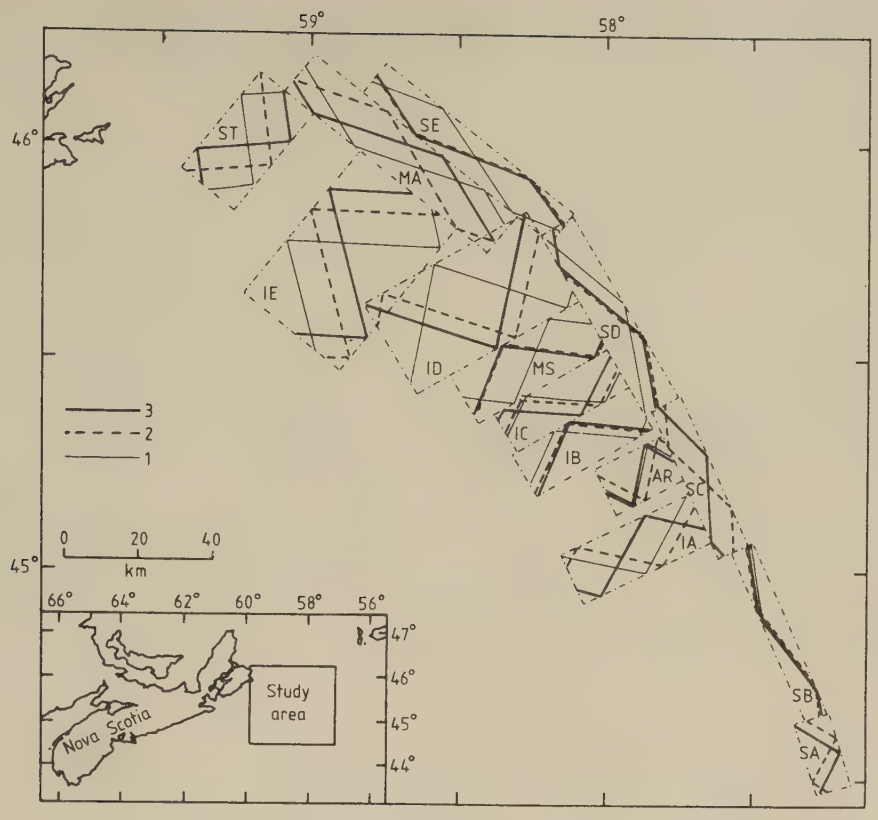


deviations in stratum size do not vitiate the method and the number of strata should be at least 20 to allow a minimum of 10 degrees of freedom in the estimated variance (Cochran, 1963)".

Figure 75 shows a design for the same stock, but over the winter period. The anticipated area of occurrence is stratified, and a replicate random design constructed with proportional sampling. Three transects per stratum were planned with additional transects to be allocated to more variable strata either during or after the end of the first coverage.

The examples given above illustrate some possible strategies and design of surveys for 5 different stock/environment situations. They are only intended to give a general idea and overview of the subject and have been selected particularly to emphasise the need for a non-abstract approach to the acoustic survey design. Experience so far has amply demonstrated that the biological and behavioural features of the individual target stocks can vary greatly as does their survey environment and hence the design criteria.

Figure 75



8.3 Standardisation of Control Settings

8.3.1 Echo-sounder

When a scientific echo-sounder is operated in conjunction with an analog integrator and manual data logging is performed, all operating controls should be kept in the optimum or standard positions to the maximum extent possible. This is important for maintaining uniformity of data collection, minimising equipment operational errors (see section 9.2) and to facilitate comparison of data between two or more survey vessels. Equipment manufacturers usually give detailed information about the functions of operational controls but they do not recommend standard control settings as these can only be established through calibration and extensive field experience with the equipment. A few general guidelines are offered below for standardization purposes with special reference to the Simrad EK sounders.

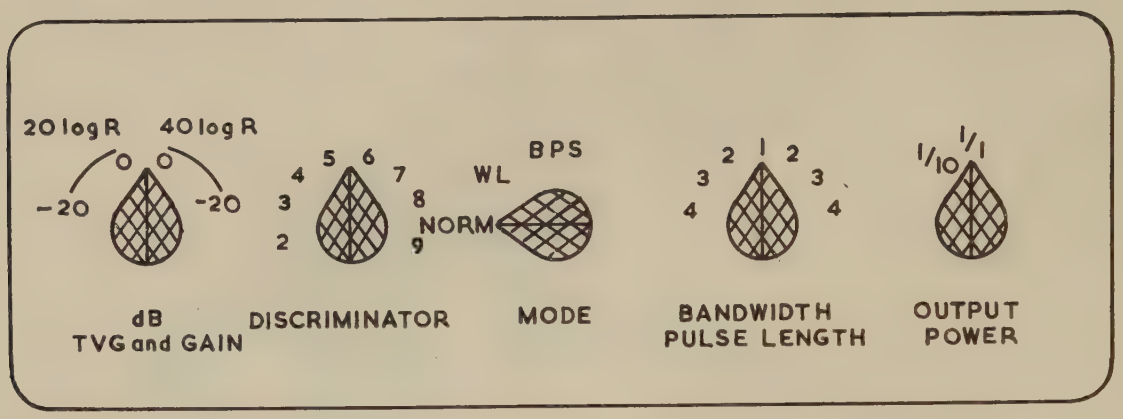
Frequency:

Selection of frequency is a simple matter of control setting in dual-frequency echo-sounders. Otherwise one integrator can be switched between two echo-sounders of different frequencies, eg. 38 and 120 kHz. The choice between frequencies depends mainly on the depth distribution of the fish and to what extent they may be mixed with planktonic organisms. If a depth range of about 100 m is sufficient and plankton is relatively abundant the 120 kHz echo-sounder should be selected because of its superiority in filtering fish echoes from the undesired plankton returns. Section 9.8.7 explains how small organisms tend to resonate at the lower frequencies. When a range of several hundred metres is required 38 kHz is necessary.

Transmitter Power:

Figure 76 below shows the front of an EK Transceiver together with the relevant operating controls

Figure 76 EK Transceiver Controls



The transmitter control has a position for 1/10 and 1/1, ie. maximum power. In practical integrator surveys the 1/1 position should be adopted as a standard to ensure efficient echo detection by maximum signal-to-noise ratio unless consistently dense schools cause blocking of the receiver.

Receiver Gain:

The maximum gain (0 dB) position should be used as a standard under all normal conditions. In extreme cases however, when an echo-sounder with particularly high performance (SL + VRT) is used on a fish stock with extremely high schooling densities ($3 - 4$ kg/m^3), it will be necessary to reduce the gain to the -20 dB position.

Time Varied Gain (TVG):

The standard is ($20 \log R + 2 \alpha R$) for integrator measurements of fish density. Only when making single fish TS measurements should ($40 \log R + 2 \alpha R$) be used.

Pulse Duration:

A short pulse duration of 0.6 ms is recommended because long pulses contribute to an increase in integrator output variance and reduction in target resolution. However a short pulse duration reduces the signal-to-noise ratio (Ehrenberg, 1971) and (Bodholt, 1977). Where a 120 kHz echo-sounder is used and there is a mixed fish-plankton layer, a reduction to 0.3 ms may be preferable on the basis of careful experimentation.

Recorder Gain:

Whilst excessive gain may result in echo recordings which are confusing and difficult to interpret, the other extreme with low gain will not permit detection of the smaller fish species. Depending on the biological characteristics of the fish stock(s) and the overall performance of the equipment, a suitable standard gain may vary from 5-7 position, the exact gain level to be determined through field test.

Discriminator Control:

This control is complicated in operation and cannot be standardized. In principle it should be in a high enough position to ensure a stable bottom pulse (seabed echo, white-line), but sufficiently low to avoid such pulses being initiated by the dense fish concentrations. These competing requirements are often impossible to fulfil, but the strategy for the operation of this control is detailed in sections 9.2.2 and 9.2.4.

Receiver Bandwidth:

The recommended standard is 'Wide' for all echo-integration work. A 'Narrow' bandwidth may result in a significant portion of the received pulse energy being blocked in the receiver bandpass filter, and thus introduce bias in the observed integrator values.

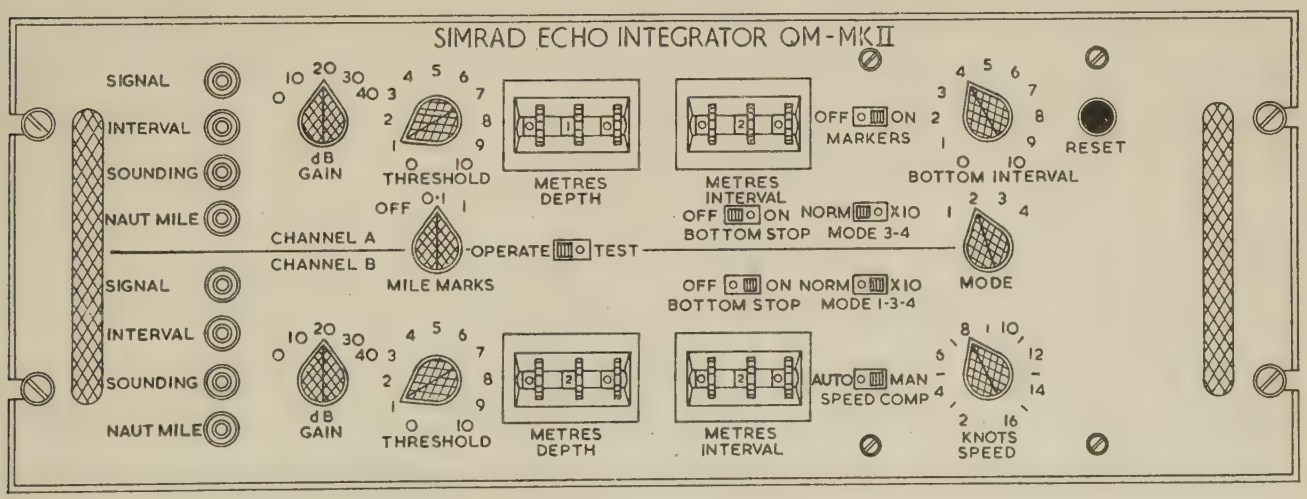
Transducer Beamwidth:

The 38 kHz EK-sounders are commonly served by dual beamwidth transducers. Selection of a 'narrow' beam is done by the Transducer Selector (Figure 76) in position 1, with position 2 corresponding to a 'wide' beamwidth. It is not possible to specify a standard setting for this control but the criterion is to use wide beamwidth when surveying shallow-water areas (< 50 m) and narrow beam for echo-integration in deeper waters. Increased beamwidth and hence pulse volume reduces variance in the integrator output.

8.3.2 Echo-integrator

With reference to Figure 77 only the most strategic operator controls will be discussed below in terms of standardization.

Figure 77 QM - Integrator Controls



Gain Control (1A and 1B):

Two factors determine the selection of integrator gain

(a) the overall performance (SL + VR) of the corresponding echo-sounder

(b) the dynamic echo levels returned by the target fish stock.

The latter factor sets the limit as to whether two independent channels (A and B) can be used with the same gain setting or, if they must cover the whole depth layer of interest but need different gain settings to cope with the relevant dynamic range. Experience indicates that a gain of 10 dB or exceptionally 20 dB, is the most common setting. Clearly this must be modified to suit local conditions encountered at a particular time.

Scale Expander (x10):

Invariably this control is kept in a standard position (x10), ie. to expand integrator deflection by a factor of 10. The advantage of the scale expander is that it ensures adequate resolution in integrator readings at low densities without necessitating an increase in gain, which in turn invites saturation errors when the densities suddenly change.

Threshold:

This control should never be used if it can be avoided. The setting requires special caution, particularly during the integration of low densities and/or when relatively small fish makes up the target fish stock. A common practice to determine the optimum setting, is to display the envelope detected echo signal from the echo-integrator on an oscilloscope screen and carefully study the level at which the different echo components are rejected in response to a gradual increase in threshold settings on a scale 0-10. Subsequently the oscilloscope picture is compared with the corresponding echo recording (assuming that the 'Recording Gain' has already been adjusted so as to give the most representative recordings of the fish stock under study). The threshold control is then adjusted to a level whereby the faintest fish echoes just exceed the threshold setting. This is largely a subjective decision making process which has to be learned through experience and is really only applicable to relative abundance surveys. Common settings range from 0.5-3.0, also depending on the integrator gain setting as shown in the manufacturers specification. Replacement of the variable control by a switch system is strongly recommended.

Depth and Interval controls (2A and 2B):

These two controls are operated almost simultaneously to set the upper and lower depth limits of the layer to be integrated according to pre-established requirements. Changes in vertical distribution of the fish may cause the equipment operator to modify these settings during a survey. The minimum depth setting is determined by the start of the effective TVG range (usually 2-3 m depth below the transducer) and this may require adjustment, eg. to 10 m as a result of near surface noise created by turbulent water in adverse sea conditions. As for the lower limit it may be automatically changed by the intrusion of a bottom echo when a survey vessel is approaching shallower waters. If the

bottom is very uneven (rugged), rocky or coral bottom, the bottom stop function may fail to work adequately (see section 9.2.2) and thus oblige the operator to switch to manual control of the lower limit at some safe distance from the seabed echo.

8.4 Data Collection

8.4.1 List of Equipment Factors

After the controls of the echo-sounder and echo-integrator have been set, or reset, it is essential to see that the correct factors are recorded for use in subsequent calculations. A list of these factors can be arranged so that it is easy to glance down and to select the figures to be used in the final calculations of MVBS ($\bar{S}_v$) and fish density ($\bar{\rho}_v$).

EQUIPMENT FACTORS

Echo-sounder frequency (kHz)

Absorption coefficient: α (dB/km)

Maximum TVG range: R_o (m)

TVG gain: ($20 \log R_o + 2 \alpha R_o$) (dB) A

Performance of echo-sounder: (SL + VR) B

(determined through calibration on standard sphere.
Note that VR includes the gain of the receiving amplifier.)

Pulse duration: τ ms

Speed of acoustic waves c, m/s

Pulse length (m) = $c\tau \times 10^{-3}/2$

$10 \log (c\tau/2)$ C

Equivalent beam angle: Ψ (steradian)

$10 \log \Psi$ (dB) D

Mean width of integrated depth layer: $\overline{\Delta R}$ (m)

$10 \log \overline{\Delta R}$ E

Elementary Sampling Distance Unit: ESDU (n.mile)

10 log (ESDU) (dB) F

Fundamental QM gain factor by design: 1.54 1.54

10 log 1.54 G

QM Scale Expander: SE (factor x1 or x10)

10 log SE H

QM gain setting: QM_{gain} (0, 10, 20 or 30 dB) I

Identifying $X = (20 \log R_o + 2 \alpha R_o) - (SL + VR) -$
$10 \log (c\tau/2) - 10 \log \overline{\Delta R} - 10 \log (ESDU) -$
$(10 \log 1.54 + 10 \log (SE) + QM_{gain})$ ..... (79)

Then, the MVBS for one depth channel $\overline{(\Delta R)}$ is

$$\bar{S}_v = 10 \log M + X \text{ (dB)} \quad \text{..... (80)}$$

and

$$10 \log \rho_v = 10 \log M + X - \overline{TS} \text{ (dB)} \quad \text{..... (81)}$$

finally

$$\rho_v = 10^{0.1(10 \log M + X - \overline{TS})} \text{ fish m}^3 \quad \text{..... (82)}$$

where M is the observed integrator deflection in mm, corresponding to conditions specified by (X) and the mean target strength $(\overline{TS})$.
Following the above-listed factors, the lumped logarithmic factor (X) can be readily calculated from the formula

$$X = A - (BCDEFGHI) \text{ ..... dB}$$

To conclude this section it should be pointed out that although the primary use of the Equipment Factors Sheet is to facilitate final calculations of mean volume back scattering strength (MVBS) and fish density, it is also a useful device to make quick checks on the effects of variability in any given quantity represented in eqn. (79). Thus, if for example the source level (SL) of the echo-sounder suddenly drops by 3.6 dB and the QM gain was increased by 10 dB without our knowledge, the resulting error would be

$$\Delta X = \Delta QM_{gain} - \Delta SL = 10 - 3.6 = +6.4 \text{ dB}$$

which according to eqn. (82) would over estimate the density (ρ_v) by a factor

$$\frac{\rho_{v_{apparent}}}{\rho_{v_{true}}} = 10^{0.1\Delta X} = 10^{0.1(6.4)} = 4.37$$

8.4.2 Data Recording and Storage

In addition to the survey planning and operational strategies described in the fore-going chapters, it is necessary to select the elementary sampling distance unit (ESDU). This is the standard out-sailed distance unit to serve as the statistical sample of the survey. The size of the ESDU is closely related to the scaling of the survey.

Thus, for a small-scale survey (relatively small area distribution of the target stock), an ESDU of one nautical mile may be chosen but for a large-scale survey covering an area of perhaps 50,000-100,000 nautical square miles, an ESDU of 5 nautical miles could be adopted as a statistically suitable sample. It should be noted that the sample size does not exclusively depend on the survey scale since its statistical efficiency is also closely related to the time-space characteristics of the fish stock distribution. A small ESDU is preferred when surveying relatively little known stocks and then, on the basis of the subsequent data analyses to determine the optimum ESDU for future surveys in the same area.

With the ESDU established and the survey under way, the incoming data are recorded at the end of each ESDU completed. If there are no automatic trigger pulses from the ships log the corresponding reset button on the echo-integrator and the marker of the echo-sounder are operated manually to define the ESDU intervals on the respective chart papers. In terms of time intervals such resets would, for example, be made every 6 minutes on a survey vessel cruising at a constant speed of 10 knots, given a one-mile ESDU. Following each reset, the two chart papers are properly annotated and the relevant data entered on an acoustic log-sheet. The format and the amount of information accomodated by acoustic log-sheets can vary considerably but the basic role is the same, ie. to provide a systematic and detailed record (or listing) of all relevant information yielded by the acoustic survey. The acoustic log-sheets represent the end-product of a survey cruise, containing data and other information categorized as follows:

1. Identification of cruise
2. Complete specification of the survey samples
3. Convenience data
4. Other data.

Category (1) generally specifies the type of survey, the cruise number, and on which vessel it is carried out, together with other characteristics of the survey exercise.

Category (2) forms the essence of the log-sheet.

It records the time of occurrence, provides an estimate of a three coordinate position (Latitude, Longitude and depth range), and one scalar property of each elementary sample, eg. the deflection in mm on the QM-integrator. Thus the log-sheets should contain one column for each item of the above information and one line (row) for a single entry in the log.

Category (3) includes data such as transect number and echo-paper roll number, etc. The latter is convenient, for example when a photograph of an echogram between two log-marks has been made during a survey and it is desired to compare it later with the original which can be found readily.

Category (4) may include columns for (a) 'Remarks' where visual observations are recorded, (b) sea surface temperature, (c) a footnote column and rows for continual verification and recording of standard control settings, and (d) station record for each time

the ship is stopped to make scientific or other observations, with information on position, weather, gear used etc.

Data storage:

In its simplest form, this would be limited to a physical storage of the raw data material consisting of a stack of log-sheets and the corresponding echo-sounder and echo-integrator chart papers. Although this is apparently a trivial matter it must be remembered that when moist echo-paper is used, recording may fade rapidly and disappear (within hours or even less) in a hot and humid tropical climate. Thus to preserve and securely store the original records it may be necessary to install a special heating device for immediate drying of the paper before allowing it to enter a take-up spool. Subsequently, it should be kept in a relatively dry and cool place away from exposure to light. Such arrangements make it possible to preserve the details of the original recordings during a period of many months or even longer.

A different storage of data is related to the use of a computer in conjunction with the QM-integrator. The analog output can then be converted into digital form for further processing and possible storage in various other forms (see Chapter 10 on Data Handling and Processing).

9. SOURCES OF ERROR IN THE ESTIMATES

9.1 Systematic/Random Errors

Statistical considerations play a role in connection with physical measurements since the latter involve an error, or inaccuracy caused by small systematic and/or random disturbances which cannot be completely eliminated. Thus, measurements of quantities such as length, pressure, voltage and temperature (factors of great concern to the acoustician), involve errors caused by the nature of the physical measurement. This is because the person who performs the measurement, the instrument used, and the system to be measured, are all affected by small unpredictable disturbances. It is to be expected that a process involving an acoustic system as the 'measuring instrument' has potential sources and causes of errors because the actual quantification of fish echoes is achieved through remote-sensing, and the physical quantity to be measured is related to a mobile, living thing. As a result, the error of measurement, or error of observation, associated with acoustic measurement and the subsequent estimates of biomass are factors of prime interest to the research worker.

Acoustic samples taken during measurement of fish stock density, and consequently, statistics derived from these samples, are subject to the two kinds of errors implied above, ie systematic errors (biases) and random errors. Both kinds of error may enter into the selection of the observations and into the values (eg integrator readings) of the observations.

Systematic errors are those that cause a bias. Acoustic measurements are often affected by a number of biases that can be either additive, or may combine so as to cancel one another. In this connection it is important to note that statistical formulae for standard error and test of significance, cannot be applied to provide an estimate of the direction or magnitude of systematic errors in the selection of acoustic samples. Systematic errors associated with acoustic surveys can often be detected and corrected by an overall logical examination of the measurement/estimation process, a fact underlining the great importance of training and the field experience necessary to attain the desired level of proficiency in this field.

Contrary to the systematic errors, the random errors are related to probabilistic considerations, this is the reason why they are often referred to as statistical errors. The level and instantaneous direction of these errors (variations showing no reproducible pattern) cannot generally be predicted and hence they cannot be avoided or eliminated. However, their effect can be understood on the basis of a theory of statistical errors first developed by Gauss and Laplace. Since then a huge volume of statistical literature has come into existence, providing in-depth analysis of random errors. Thus, to familiarize himself with the related formulae and parameters involved such as arithmetic mean, standard deviation, variance, coefficient of variance and the confidence limits about the mean, the reader is referred to the recommended literature on the subject. Finally, as an important conclusion from the above, it should be noted that while random errors govern precision, the accuracy is governed by systematic errors.

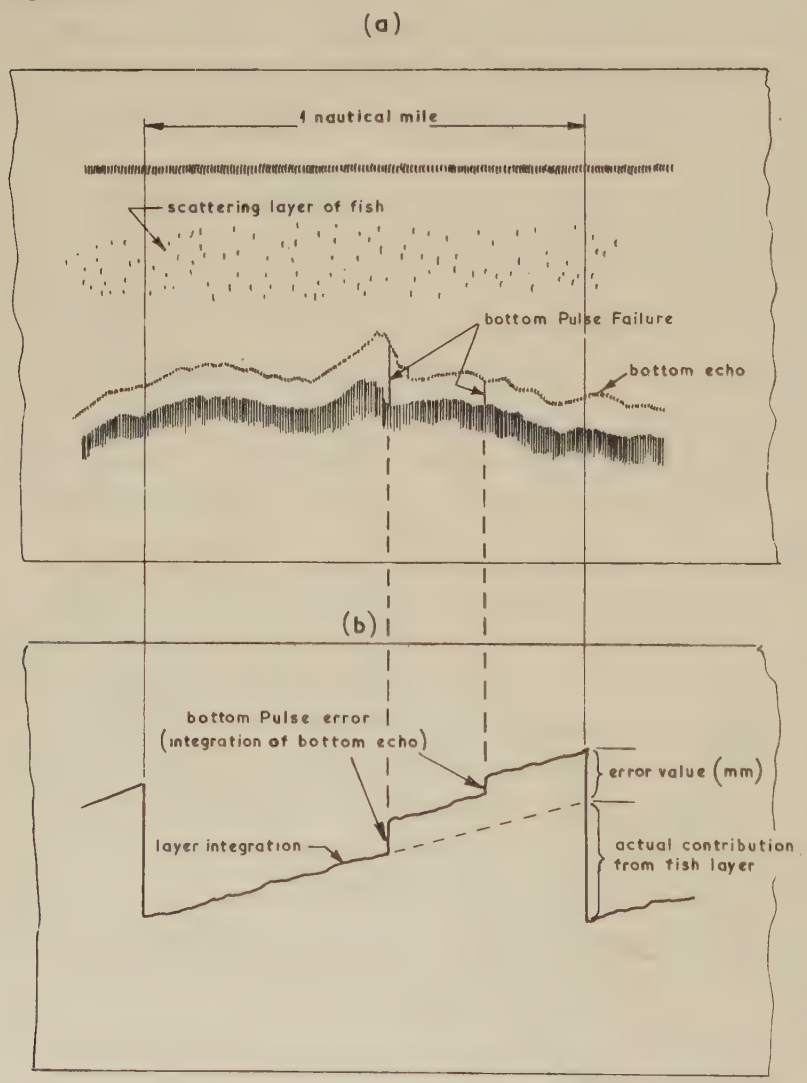
9.2 Equipment Operational Errors

Experience over the past 12 years or so, since acoustic equipment became a quantitative tool in fisheries research, has demonstrated that extreme care is required in operating the equipment (scientific sounders and integrators) to avoid unnecessary errors in the fish abundance estimate. To monitor and correct operational errors, or better still, to take preventative measures to avoid their occurrence, requires skill only properly learned through experience. However, a prior knowledge of the nature of these errors is helpful in putting the problems into perspective. The following sub-sections summarize the problems involved and explain how corrections can be made.

9.2.1 Bottom Pulse Failure

When the echo-sounder fails to produce a bottom pulse for each sounding (ping), there will be no integrator bottom stop function; thus the bottom echo will be integrated as a false fish echo. This only happens if the lower depth limit of a selected integration interval is set below the actual sounding depth, and when the 'Bottom Stop' control is in the 'ON' position.

Figure 78



This kind of error is commonly observed under the following conditions:

1. very uneven (rugged) rocky or coral bottom
2. extremely steep sloping bottom
3. bad sea conditions (vessel rolling and pitching)
4. exceptionally 'soft' bottom sediment.

A typical situation is illustrated in Figure 78 alongside, which is largely self-explanatory.

It will be readily understood that errors of this kind can reach major proportions if not kept under reasonable control by the equipment operator. Such a control can be exercised in two ways. Firstly, the operator should maintain the 'Discriminator' control in a relatively high

position (6-8). This improves the response of the system and increases the chance of reliably generating the bottom pulse function. Secondly, if this does not minimize the problem sufficiently, change to a manual control of the integration interval lower limit, regularly operating the 'Interval' thumb-wheel selector. In the latter case, a problem arises when the fish concentration of interest is located on, or close to the sea-bed, when it may be difficult to follow the contour of the latter. Also the thumb wheel switching creates 'spikes' (explained in the following section) that cause false integration. As the reader will gather from the above, minimizing the described error, can only be learned through field experience.

9.2.2 Layer Selector Spike

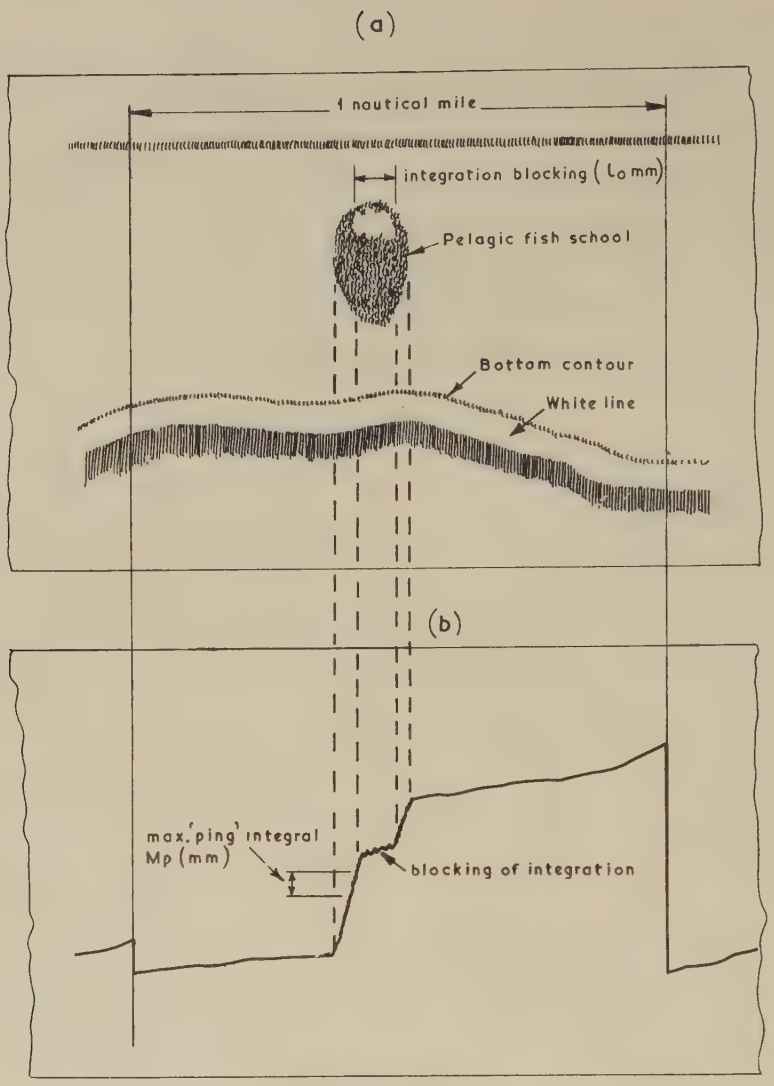
This particular error is caused by an undesirable side-effect in the thumb-wheel selector of the QM echo-integrator, which, when rotated, generates an electrical spike and this is picked up by the integration circuits. A false fish echo integration results which appears on the integram in much the same way as the bottom echo shown in Figure 78. Apparently the only way for the integrator operator to avoid this problem when using the standard QM, is to manually time the actual rotation, so as to let it occur when the rotating EK recorder stylus is not in contact with the recording paper. This effectively ensures that the integrator is 'OFF'. The problem can be cured and other improvements made to the QM integrator which increase the dynamic range and reduce drift.

9.2.3 School Generated Bottom Stop Pulse

While the two errors explained above (9.2.1 and 2) result in apparent false fish echo integration, and hence positive bias, the School Generated Bottom Pulse Error (hereafter SGBPE) always brings about negative bias due to blocking of the fish echo integration. In principle, this kind of error occurs because the EK echo-sounder is sometimes unable to make a physical distinction between a fish school and a seabed; it can only distinguish between low and high echo levels. Consequently, when the sounder is operated in a white-line mode and detects a very dense fish school exhibiting similar target strength to that of a seabed (say, TS = 20 dB), the 'sharp', strong echo returned from that school will be indistinguishable from a seabed echo. A 'bottom pulse' will be generated, resulting in complete blocking of integration until the next transmission takes place. For a better illustration of the problem, consider Figure 79, which shows (a) the theoretical recording of a very dense pelagic school on the echo-sounder recorder, (b) the corresponding graphic integrator output (integram), and (c) the geometric cross-section of the school that has been effectively blocked from echo-integration during the survey vessel's traverse time.

As seen in the corresponding realistic pictures, the SGBPE error can be severe. In practical survey work involving densely packed school concentrations (eg Anchovy schools off Peru, Horse-mackerel in the Black Sea, Turkey, or Sardine schools in the Moroccan waters) it can be of crucial importance. In fact, many survey operations have turned out heavily biased data due to inadequate control of such errors, and on some occasions, a considerable amount of data has had to be discarded.

Figure 79



The SGBPE error cannot be fully controlled in difficult conditions, but it is within a skilled operator's ability to keep it within acceptable bounds. To achieve such control, the following guidelines are important:

a. The operator must exercise due awareness as to the type of fish concentrations he is surveying and also check that both echo-sounder and integrator gain controls are in low positions to avoid saturation in the equipment. In practice, this means that when the overall performance of the EK (SL + SRT) is high, say, 30 dB, its gain control would be in position -20 dB. The QM integrator gain could be in the 10 dB position, or possibly as high as 20 dB, if the red saturation warning light does not indicate the need for a lower setting. In the case of a relatively low overall performance the EK gain can usually remain in 0 dB position with the QM set at 10 dB gain.

b. When gain controls are operated as above, the 'Discriminator' control usually needs to be kept in a relatively high position to ensure a steady white line recording, or, in other words, an effective prevention of bottom layer integration. Hence, there are contradictory requirements, namely, that whilst a high setting of the discriminator control helps to avoid undesired bottom echo integration, it also

invites a school generated bottom stop pulse and the subsequent SGBPE. When a reasonable compromise cannot be found for the control settings, the only solution is to manually control the integration intervals. In cases when integration blocking has already occurred, a crude correction can be made using the following procedure. Assume that a survey vessel is sailing at 10 knots, the echo-sounder is operated at a rate of 96 ping/min. and the paper speed is 25 mm/min. Integration is made over one nautical mile as the standard distance unit, corresponding to 6 min. sailing time at the given speed. Then the total number of pings per distance unit Nt = 576 and the corresponding recorder paper advance between successive one-mile log marks ℓp = 150 mm.

From Figure 79 we can define ℓ_0 as the observed length in millimetres of the school cross-section which is not integrated, indicated by the length of the white band at the top of the school trace. M_p = the maximum observed deflection (mm) for the individual pings prior to (or after) blocking. From the above, the total number of non-integrated 'lost' pings (N_p) can be calculated from the relationship

$$N_p = (N_t \ell_o/\ell_p)$$

Assuming that ℓ_o = 4.7 mm, $N_p = 576 \times (4.7/150) = 18$ pings.

Knowing N_p and assuming that M_p is representative of the 'lost' mean ping integrals from the school cross-section, the total correction, or lost integrator school reading M_c, can be calculated from

$$M_c = M_p \times N_p$$

Hence, for M_p = 4.5 mm the correction, $M_c = 4.5 \times 18 = \underline{81 \text{ mm}}$.

9.2.4 Secondary Echo Interference

This form of echo interference is a special problem. For the present purpose it is defined as echoes received in one transmit/receive period which were initiated by the previous transmission. It occurs, both in marine surveys conducted in shelf seas, and in those carried out on large lakes. The magnitude of the positive bias error introduced by this effect depends on the relative depths of the fish distribution, the bottom and its reflecting strength, plus the overall performance of the echo-sounder as well as the depth range on which it is operated.

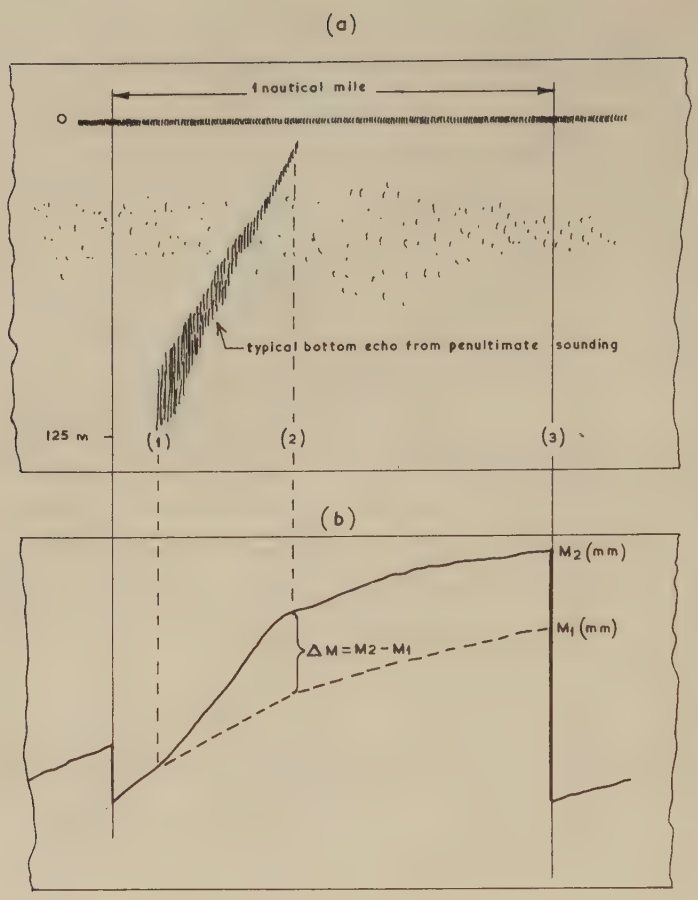


Figure 80 depicts the problem and shows the principal error introduced into the integrator observation (M).

For an example of this problem, assume that an echo-sounder is being operated on a range of 0 - 125 m, ie a pulse rate P_r of 96 pings/minute. This means that the time between the start of each transmission is

$$T_t = 60/P_r = 60/96 = 0.625 \text{ seconds.}$$

During this time interval a transmitted pulse can travel a total distance in the water of

$$d = \text{speed} \times \text{time}$$

Hence, for this time interval and using 1500 m/s as the approximate speed of acoustic waves one obtains

$$d = 1500 \times 0.63 = 937 \text{ metres}$$

ie an indicated (true) depth of 937/2 = 468 metres.

Taking this distance as the actual depth and considering the echo-sounder pulse train P_1, P_2, P_3, P_4, ... P_n (96 pulses per minute), it will be realized that the penultimate pulse, say P_3, will return its detected bottom echo at the same time P_4 is being transmitted. More generally, if the bottom depth varies in range from d_1 = 468 m to d_2 = 468 + 125 = 593 m, the second bottom echo can theoretically interfere with any other echo occurring in the basic range interval 0 - 125 m. The echogram (a), corresponds to a situation where the bottom depth has theoretically varied from 593 (point 1) to approximately 470 m (2). As indicated, the bottom trace appears strongly at the end of the 125 m scale and then gradually weakens until it usually fades out at, say 20 m range. This is due to the effects of the Time Varied Gain (TVG) function of the receiver. If

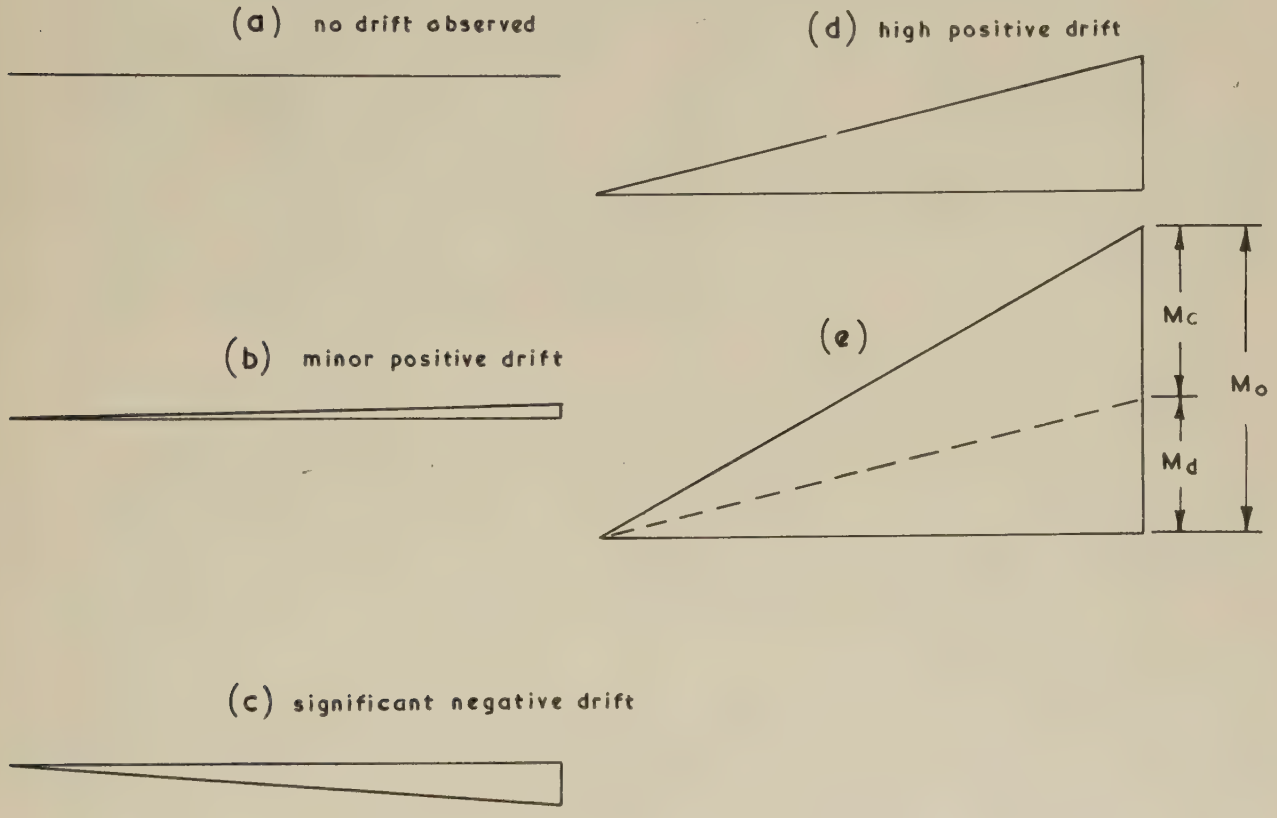
the bottom depth had been a constant 520 m, the penultimate bottom echo trace would have been recorded as a relatively faint bottom at a constant depth of 50 m on the 125 m scale. Figure 80(b) illustrates the theoretical contribution to the integrator output of the unwanted bottom echo, resulting in an error reading of $\Delta M = M_2 - M_1$.

The only measures the equipment operator can take to minimize such problems is to change the sounding rate, (depth range), and possibly the integration interval(s) according to the distribution of the fish surveyed. Further ways of dealing with the problem may be learned at sea.

9.2.5 Instrument Drift

One of the problems associated with the operation of the QM echo-integrator quickly encountered by the user, is the so-called 'drift problem'. This is caused by inherent limitations of the analogue circuits involved. Its symptoms are observed as variations

Figure 81



in the integrator output (mm deflections) when no echo-signal is present, ie when there should be no deviation of the QM recorder stylus from its zero position over a given time interval or distance, eg one nautical mile. The level of drift is generally affected by ambient conditions (temperature and humidity) and it may appear as a negative, or a

positively sloped graph on the recorder. The slope coefficient may remain fairly constant over long periods of time, but it sometimes has a tendency to cyclic variation with time, eg diurnal variations.

A pictorial presentation of the drift problem is presented in Figure 81(a-e). Whilst illustrations (a-d) are self-explanatory of the drift characteristic, illustration (e) is intended to show the relationship between an observed integrator reading M_0, the mm deviation caused by the drift M_d and the mm component of the fish echo M_c which contributed to the observed reading. Given these, we can define the relative drift error E_d as the ratio (M_d/M_o) or, in more general terms, the error in percentage can be expressed as follows:

$$E_d = \frac{M_d}{M_o} \times 100 = (1 - \frac{M_c}{M_o}) \times 100 \quad \text{(percent)}$$

From this formula it can be inferred that, when large, dense, fish concentrations are being measured ($M_o \cdots M_d$), the drift error is likely to be insignificant, where in low-density situations ($M_o \sim M_d$), the error caused by the drift can be of major magnitude.

Knowing the nature of, and what generally governs the level of the drift error, the reader may ask what can be done to exercise control over it. The answer to that question is two-sided; firstly, the service, or acoustic engineer responsible for the survey equiment must make due effort to ensure that all relevant circuits of the system are adjusted for optimum performance. Secondly, it is the role of the operator (and the data analyst) to carefully monitor the drift 'behaviour' during a survey exercise, and thus be able to separate the M_d component from the observed integrator values, to permit a reasonable post correction of these data. For digital integrators this is not necessary.

9.2.6 Attentuation by Bubbles

Attentuation of acoustic waves, due to wind induced bubbles in the upper layers of the sea, is a problem which can affect both hull-mounted and towed transducers. Recently, investigations have been made by Novarini and Bruno (1982) into the influence that such attenuation may have on echo-integration surveys. Their study covered frequencies of 8-60 kHz and wind speeds up to 30 knots, providing evidence that attenuation due to this effect starts at a lower wind force and is of greater magnitude than hitherto reported for shallow transducers.

Many surveys are carried out in weather conditions up to wind force 7 on the Beaufort Scale (35 knots). In order to maximise the efficiency of a survey, the ship must be run at the fastest speed possible for the prevailing conditions. It is also important to maintain the accuracy of the results to the greatest possible extent, thus any legitimate correction available should be applied.

Figure 82 is drawn from Novarini and Bruno's equation 9. It shows a rapidly rising attenuation, 6 dB per 7 knot increase in wind speed at 38 and 120 kHz when the transducer is only 1 m deep.

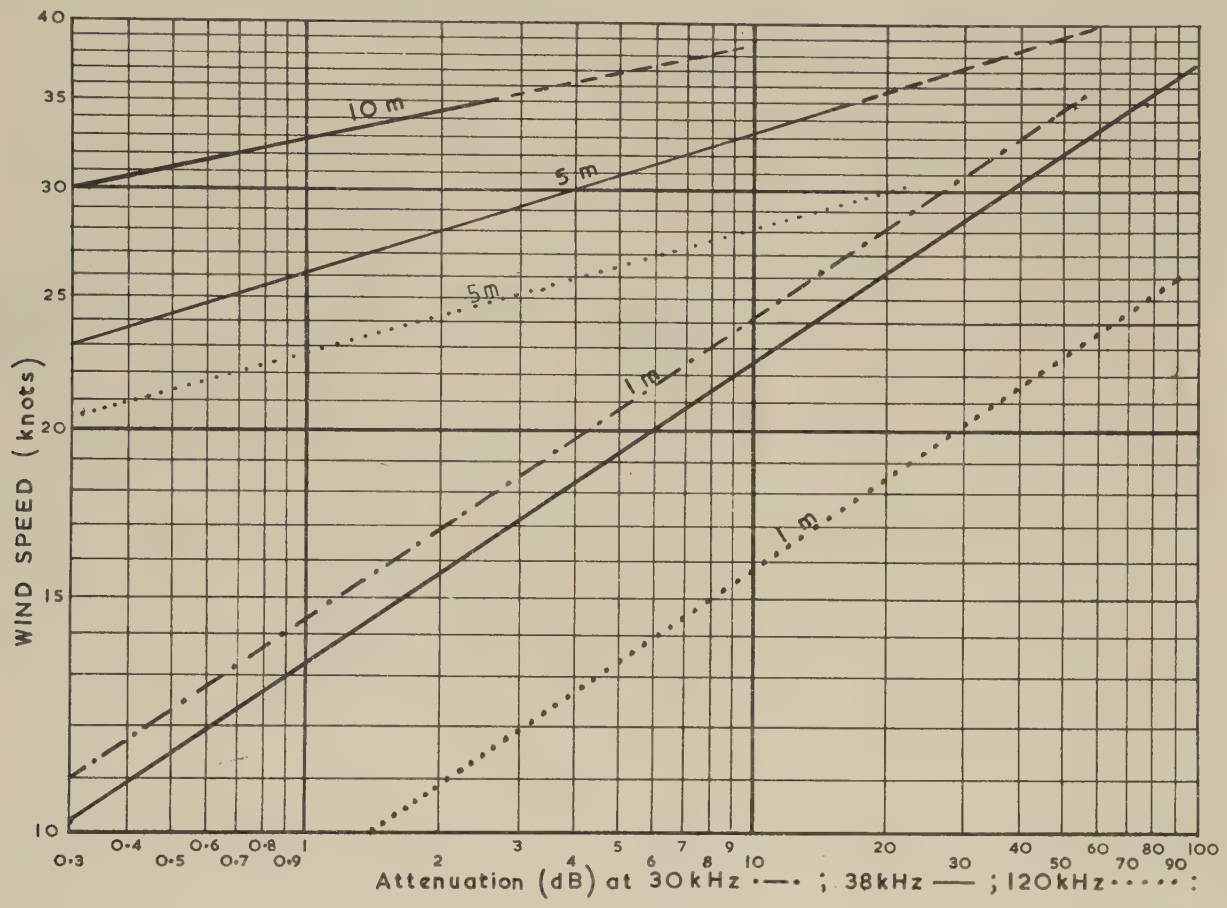
The rate of change of attenuation is 9 dB per 7 knot when the transducer is at 5 m depth but there is less than 0.3 dB loss until the wind reaches 23 knots. It should be

pointed out that the authors only claim validity for their formula in the frequency range 8 kHz $\leq f \leq$ 60 kHz and over the wind speeds of 6 to 30 knots. Nevertheless the results at 120 kHz are not dissimilar to those published by Dalen and Lovik (1981) although the latter authors include bubbles other than those from wind generated sources.

The authors of these papers point out that users of high-frequency echo-sounders should especially be aware of this possible source of serious error.

This is another case where the use of a towed transducer could be beneficial.

Figure 83



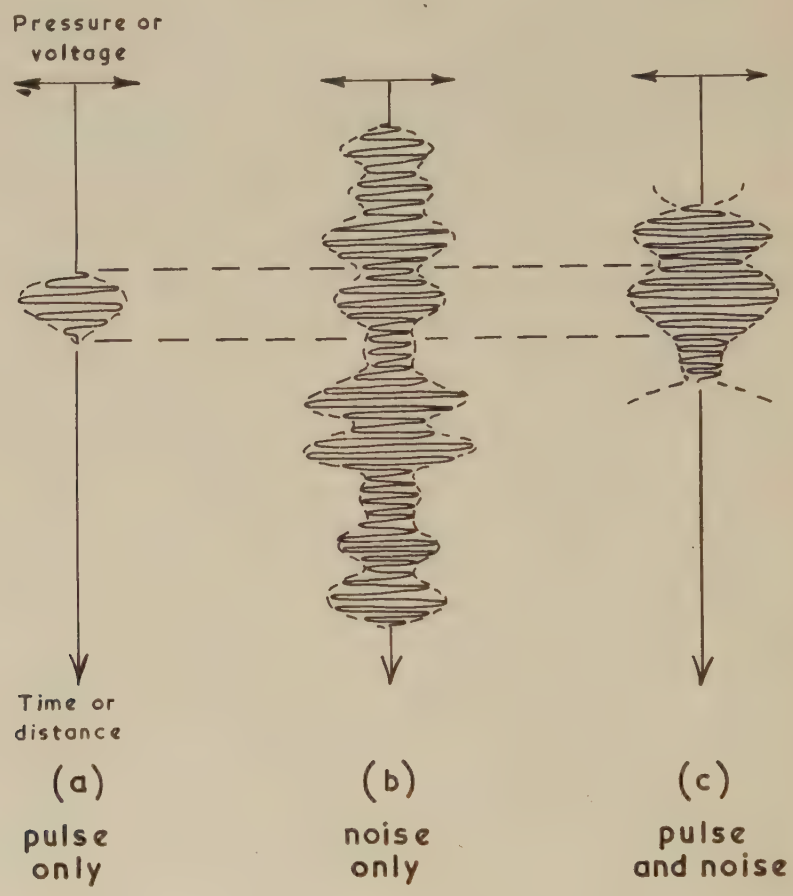
9.3 Noise

A simple definition of noise states that it is the cause of any unwanted power output from the receiver amplifier, regardless of the source. Note the emphasis on the word unwanted. Noise can arise from electrical sources, or from the sea state, but by definition any target, or targets, not being sought give rise to noise. Naval forces seeking submarines may regard schools of fish as noise, scientists surveying for schools of fish might consider the signals from plankton as noise. What we want to avoid is the recording of any form of signal which might give a false estimate of the particular type of biomass we are seeking.

With experience a paper record can be used to interpret signals sufficiently well to differentiate between electrical, or acoustic noise which is not synchronised to the display and, sometimes, the signals from small organisms. It is evident from section 9.7.7

that for some sizes of organism at certain depths, the acoustic echoes are magnified considerably.

To function correctly, acoustic systems must have high sensitivity, ie the receiving transducer and the amplifier must respond to very small echoes. This makes them prone to interference from quite low levels of acoustic and electrical noise generated on or near the ship. Noise is rarely confined to one frequency, or even to a narrow band of frequencies, it tends to be spread widely, but its effect on system performance is limited to the amount of noise power occurring within the operating bandwidth of the echo-sounder transducer and receiver amplifier. The effect of a high level of noise on a pulse is shown in Figure 83 below.



9.3.1 Biological Noise

Biological noise as a subject forms a part of a wider study of marine organisms which covers both their acoustic production and detection abilities. A brief review of the subject (by Tavolga) is presented in Underwater Acoustics, Albers (1967), Volume 2, but a more detailed review can be found in Tavolga (1965). In the context of the present manual, which deals with the practical application of acoustics to the estimation of aquatic biomass, we are concerned with the implications of two noise categories; these are:

a. intense noise; for example that emitted by a school of porpoises which produce a strong noise trace on the echo-sounder recorder and causes biased readings on the integrator.

b. the stridulatory noise (rubbing and rasping) such as that produced by crabs, shrimps or lobsters which, in special circumstances, may give rise to an error in integrator observations and/or introduce confusion in the interpretation of echograms.

The latter category (b) may not be of immediate concern in acoustic survey work, but it is sufficiently significant to make the reader aware of possible implications. According to Tavolga (1965), the individual clicks of snapping shrimps are quite powerful and at a distance of one metre may attain an intensity of over 150 dB//1μPa.

The ambient noise level produced by a concentration of shrimps can reach levels of up to 140 dB//1μPa. In the case of the warm-blooded mammals (toothed whales) such as porpoises, dolphins, pilot whales, etc, they emit high-pitched whistles, or squeals, whose pitch varies from about 1,000 to 10,000 Hz, (some dolphins go higher than 200 kHz). The large baleen whales that feed upon plankton by filtering water through their mouths are known to produce a variety of sounds of a harmonic type, most of which have fundamental frequencies below 400 Hz.

From these few examples it will be clear that an aquatic survey environment is not acoustically quiet and that noises of biological origin can sometimes play a role in acoustic measurement errors.

9.3.2 Electrical Noise

This may be generated by electrical machines, in which case it could be conducted to the echo-sounder directly through the wiring, or, it may be reradiated as electromagnetic waves and be picked up on the transducer/amplifier wiring at the most sensitive parts of the system. Cables carrying power, or, control signals, which are routed close to the transducer wiring may easily induce voltages of a few microvolts into the latter. It is essential therefore, to separate the transducer cable from any others as far as possible, and, to ensure that the screening and earthing arrangements specified by the echo-sounder manufacturer are scrupulously observed.

Noise entering via the power line may be related to the mains frequency. To check this, connect one of the vertical channels of the oscilloscope to the calibrated output of the echo-sounder. Set the oscilloscope trigger selector to 'mains' and select a sweep speed of 10 ms/cm. Turn up the vertical sensitivity so that the noise is clearly displayed. If it is related to the mains frequency the noise will stay in position on the oscilloscope screen. However, many frequencies may be present, so that the trace shows random movements and an estimate of the peak amplitude of these should be made.

To prevent excessive noise affecting the sounder it is necessary to locate the source and eliminate it. Identification of noise sources can be time consuming and requires much patience. The usual method of working is to first switch off as much of the machinery as possible, then reconnect one after another, the different motors, compressors, inverters, etc until the source, or sources are found. Each of these noise sources will have to be repaired, if faulty, or electrically suppressed. If the noise is from the vessel's generator it might be identified by changing over if there are two or more auxiliary engines or, if shore power is available, this might be used for a comparison.

Installation of noise suppressors on generators or their regulators is a job for a qualified electrician and should never be attempted by a non-specialised person. Voltage regulators are easily damaged if noise suppressors are not properly installed. If in doubt, contact the manufacturer of the actual generator for advice.

Some of the noise on the power line may be suppressed at the input to the sounder or within the unit itself. It is the high frequency noise, from rotating machinery, or solid-state switches such as thyristors, which interferes with echo-sounding. Often a filter at the mains input will suppress this noise. Such filters can be purchased but it is important to be certain that they have an adequate current carrying capacity before having them installed.

9.3.3 Receiver Amplifier Self-noise

The total noise measured at the calibrated output of the receiver, is due to all noise at the input, plus the actual noise generated within the amplifier itself. For practical operating purposes the total noise is significant, but it is important to be able to separate the noise of the amplifier from electrical noise picked up on wiring, and from acoustic noise arriving via the transducer.

Measurement of the EK series receiver self noise can be made as follows

Step 1 Connect a high impedance voltmeter (vacuum tube, or transistor voltmeter) to the calibrated output of the echo-sounder.

Step 2 Set the echo-sounder controls as follows:

TVG and Gain : one of the two 0dB positions
Bandwidth : narrow
Test/operate : test (no signal to test input)
Output power : 1/1

Step 3 Stop transmitting trigger

: for EK and EK-R set phased range selector to ext.
: for EK-S set basic range selector to 0.
disconnect transmitter trigger. (cable No. 6 at 11000 recorder main terminal).

Step 4 Switch echo-sounder on, the voltmeter indicates the self-noise. Note result.

Step 5 Change to wide bandwidth, note voltmeter deflection. Normal values below:

Frequency	Typical Noise Levels, Calibrated output			
	Narrow Bandwidth		Wide Bandwidth	
12 kHz	-61 dB/V	0.9mV	-55dB/V	1.8mV
18	-59	1.12	-53	2.2
38	-59	1.12	-50	3.2
50	-59	1.12	-49	3.5
120	-54	2.0	-48	4.0

There is no point in trying to make other measurements unless the receiver amplifier noise level is normal. If it is too high, try to find out if the noise is produced by the echo-sounder, or if it enters from outside. The following measurements may help to indicate the source.

Whilst observing the voltmeter, change the power output selector from 1/1 to 1/10 and then to ext. transmitter. If the noise level drops immediately the power selector is changed from 1/1 to 1/10, then to ext. transmitter, the noise is probably electrical, originating outside the echo-sounder, perhaps entering via the mains cable, or, induced into the transducer leads. If the noise level drops slowly after changing from 1/1 to 1/10 power, the transmitter itself is probably the source. Noise is most commonly generated in this unit by the output stage, where one or more transistors may have developed a leakage.

9.3.4 Acoustic Noise

Sources of noise arise from natural causes within the sea itself, or at its boundaries. They may also arise through the movement of the ship through the water, or, from the means of propulsion. Noise due to natural causes alone is not under the control of man so it must be measured and then tolerated. It is due to rain on the surface of the sea, from waves, from the interaction of water currents with seabed material and also from thermal molecular activity at the higher frequencies. Noise from natural causes is usually regarded as ambient noise ie (all encompassing) but it is by no means constant.

The noise output from an echo-sounder may be measured at any instant of time, but many sources of noise are dynamic and the resultant levels may change quickly. Probably the most important example of this is the increasing sea-state noise as the wind force gets higher; the effect of this is to produce bursts of noise as the interaction of ship and waves becomes more violent. An associated effect is loss of signal because of aeration at the face of a hull mounted transducer. Clearly, the direction in which the ship is travelling and its speed relative to the wind and swell can make a significant difference to the level of noise and loss of signals. However, it is the high transient level of noise resulting from weather and related sea conditions which initially causes a reduction in ships survey speed, often delaying the progress of the survey until the noise level drops (if a more favourable course is not feasible).

An effect which is not well known is that found in coastal zones where there is a high rate of tidal flow. Wideband noise (certainly up to 300 kHz) is generated by the action of fast-flowing water over sand ridges, evidently causing sand particles to go into suspension where their frequent collisions generate noise. This is often evident as a 'plume' trace above the seabed echo, extending almost to the surface, but not always appearing to connect to the seabed. The noise disappears completely when the tidal flow rate drops as the direction is about to change, so for a period of nearly two hours it may not be in evidence. Minimum spectrum levels at the seabed, measured at 30 kHz and 100 kHz off the east coast of Britain were 93 dB/1μPa/1Hz and 85 dB/1μPa/1Hz respectively (Harden Jones and Mitson, 1982).

At the lowest level is thermal noise which can be detected in very quiet conditions down to about 20 kHz, but it is normally only of importance above 100 kHz, see Figure 35. Knowing the temperature of the water, the bandwidth of the receiver and the radiation resistance of the transducer, it is possible to calculate the voltage VRT at the transducer terminals which is due to thermal noise.

$$VRT = (4ktB\ RR)^{\frac{1}{2}} \quad \text{..... (79)}$$

where VRT = V_{rms} due to thermal noise

k = Boltzmanns constant 1.37×10^{-23}

t = temperature, 271 + °C

B = bandwidth in Hz

RR = radiation resistance (ohms)

Example: A transducer with a bandwith of 10 kHz, operating at a temperature of 10°C and having a radiation resistance of 800 ohms, will have a thermal noise voltage of 0.35 μV produced across its terminals, that is -129 dB/V. If the amplifier increases this by say, 60 dB, the output noise will equal 60-129, or -69 dB/V ie Antilog -69/20 = 350 μV, or 0.35 mV. The same answer is obtained if we say that 60 dB voltage gain is 10^3 times, for $0.35 \times 10^{-6} \times 10^3 = 0.35$ mV, or 350 μV.

9.3.5 Ship Noise

When wideband measurements are made of ship radiated noise, they normally show a high intensity at frequencies of a few hundred Hz, dropping steadily as frequency increases. The measurements are rarely extended above 10 kHz, so for acoustic survey purposes it is necessary to take the noise level at the output of each echo-sounder. The main sources of ship noise are machinery, propeller and flow.

Machinery noise may arise from high levels of vibration transferred through the hull into the water. The amount of acoustic energy at echo-sounder frequencies is generally low, but up to 50 kHz it may form a measurable background noise. In calm weather conditions it can set the effective threshold of the survey equipment although in most vessels this is due to the propeller noise.

When noise measurements are made at the output of the echo-sounder at various ship speeds and the results are plotted on a graph, with noise voltage on the vertical scale and speed on the horizontal, the voltage against speed is usually an almost horizontal line for slow speeds. This is probably due to machinery with perhaps a small amount from the echo-sounder amplifier. Then suddenly an almost vertical line appears; this is due to the onset of propeller cavitation. As a physical phenomenon, cavitation evidently causes the formation of bubbles by negative pressure, literally a tearing apart of the water, and the sudden collapse of the bubbles causes noise over a wide band of frequencies. Cavitation occurs at the tips, or on the edges of the propeller blades.

Damage to the blades in the form of quite small cuts can cause a considerable increase in noise at echo-sounder frequencies. It is therefore important to ensure that any rough or jagged surfaces, or edges are removed from the propeller and that all surfaces are smooth and polished after dry-docking. A well-designed propeller should not cavitate at the lower speeds, but if it does it is often possible for experts to treat the leading edges of the blades, or the tips, to prevent cavitation noise from unduly restricting survey speeds.

By the nature of their operation, controllable pitch (CP) propellers are a source of variable noise level and when measurements are made on vessels so equipped, it is necessary to repeat them for several pitch settings.

When towing a trawl the noise level is greatly increased and allowance must be made for this in a systematic way, by using the results taken with particular nets and at known towing speeds to set the increase in threshold at which the equipment is integrating. Because we are used to looking at pictures of sections through a transducer beam it is easy to forget that it is actually three-dimensional and that there are sidelobe responses which may look directly at the propeller.

Example: The seventh sidelobe of a 30 kHz transducer had its line-of-sight through the position of the propeller, with a range between the transducer and the propellor of 66 m. The response of the sidelobe was -24 dB relative to the main beam which had a sensitivity of -184 dB/V/1μPa. Thus the sidelobe sensitivity was -208 dB/V/1μPa with a directivity index of 15 dB. Noise level at 30 kHz referred to a position 1 m from the propeller = 125 dB/1μPa/m in a 2 kHz band at a ship speed of 9 knots.

Propagation loss = 20 log66 = 36.4 dB and

VRT(noise) = 125+(-208)-36.4+15 = -104.4 dB/V which is

antilog -104.4/20 = 6μV

Because the noise level due to the propeller may change suddenly during operational service it should be checked, recorded and graphed at regular intervals.

Flow noise is largely a matter of the transducer siting and the manner in which the installation is completed. If there are projections or cavities along the hull in front of the transducer they will often generate speed dependent noise. Rough edges near the transducer face due to welding, or the sides of a housing not faired sufficiently carefully to the hull can also be responsible for high noise levels.

9.3.6 Miscellaneous Sources

Acoustic interference occurs when different instruments operate on the same frequency but it is rare for this to cause any problems when the beams are directed vertically downwards as for echo-sounding. Two equipments on the same vessel, operating at the same time are likely to interfere seriously with one another and even if they are synchronised no quantitative measurements will be possible. Despite considerable frequency separation of the systems, mutual interference results because of the wide range of frequencies present in a pulse.

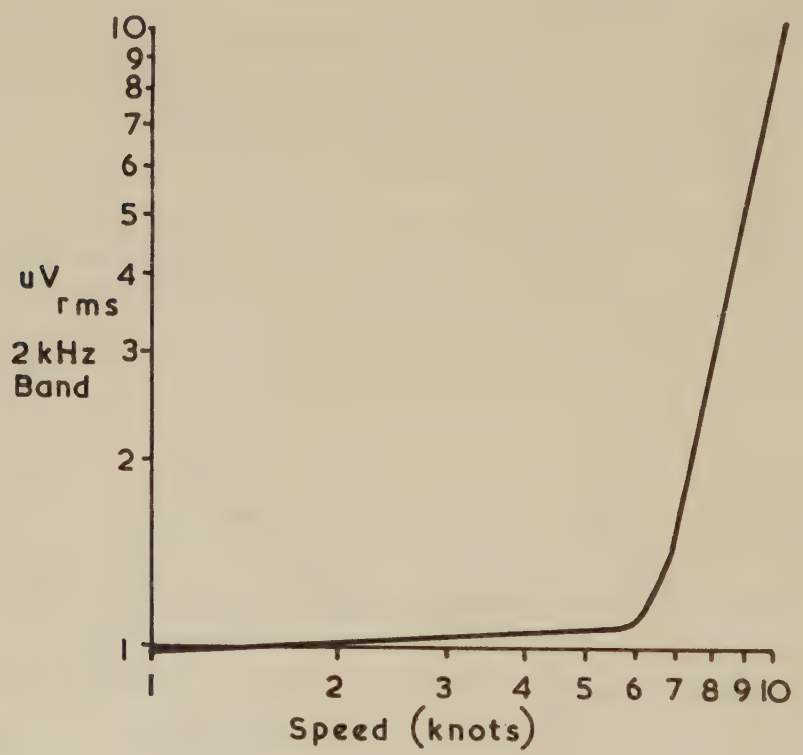
Acoustic noise measurements at sea need to be recorded in detail because there are so many variables such as weather and depth. For these measurements the depth of water should be no less than 20 m, but if possible it should be deeper and the sea calm. Depth is important because noise is reflected from the seabed, and this causes problems the extent of which depends on the level of ship noise radiated towards the seabed. Noise levels in shallow water and under bad sea conditions are also important, so the opportunity should be taken to measure these when conditions are suitable.

Normal measurement procedure begins with the engines stopped, except for auxiliaries supplying power. After initial measurements with the ship in this state, the main

engine/s is started and the measurements repeated but without the propeller turning. Results of these static measurements should be recorded in a suitable table which will also be sufficient to take those following. Next the propeller/s is engaged and the ship taken through its speed range at intervals of 2 knots, the noise level being recorded at each interval once the ship has actually reached the called-for speed. Finally the vessel is run up to full speed and the propeller is stopped. Whilst still at full forward speed the flow noise, sometimes called 'speed noise', is measured at various intervals as the speed drops.

Towed transducers need a similar procedure to be applied, although the effects of machinery noise will normally be less. It is often necessary to try the body with various lengths of cable let out in order to achieve the best position with respect to low noise pick-up.

Graphs of noise measurement against ships speed are best illustrated on log/log paper as in Figure 84. If the sensitivity of the transducer is known, plus its



bandwidth, or that of the receiver amplifier, it is possible to calculate the acoustic spectrum level SPL at the transducer face from measurements of noise voltage. SPL is the noise power for one cycle (Hz) of energy and is expressed in dB/1μPa/1Hz. This information is a useful reference against the SPL of ambient noise likely to be encountered at various sea-states. An oscilloscope or sensitive voltmeter can be used, but readings must be converted to rms and an allowance made for any gain in the system between the transducer terminals and the point from where the measurements are taken.

9.4 Coverage Errors

Acoustic surveys are based on the premise that if a ship makes a track across a given area of sea surface, the acoustic signals received from its scientific echo-sounder represent a true proportion of the biomass in that area.

There are times and situations when the spatial coverage of a given area is adequate, but for various other reasons the depth coverage of the water column is restricted. The next section discusses the inherent limitation of echo-sounders in the detection and estimation of fish close to the boundaries of sea surface, bottom and shore.

9.4.1 Near Surface Layer

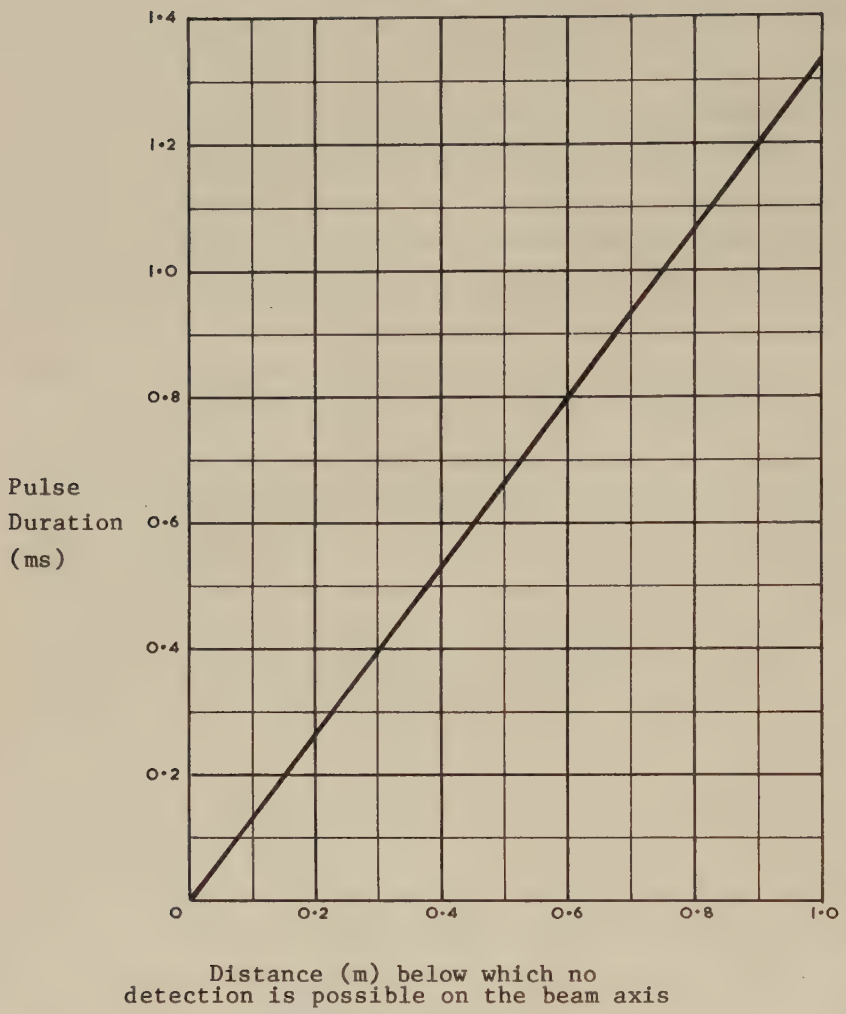
Excepting when both are perfectly flat, the surface and bottom act differently as reflectors of acoustic waves. Often the water surface is moving in a random manner, thus reflecting significant amounts of acoustic energy in different directions with respect to the transducer. Therefore it is difficult to use the water surface as a reliable reference, either in terms of its distance from the transducer, or in the stability of the signal amplitude obtained from its echo. This means that in addition to the 'dead-zone' (section 9.4.3) there is a volume of water where uncertainty exists due to wave motion and this is difficult to define.

For practical purposes of fish detection it seems likely that the greater the agitation of the water near the surface, the less chance there is of significant quantities of fish being within the volume of uncertainty. As a rough guide it might be reasonable to assume that no fish will be detected within a distance from the surface of twice the wave-height, plus half the pulse length. Another factor, associated with wave action, is the production of bubbles which may persist for long periods in the surface region. Bubbles have the effect of introducing extra attenuation in the acoustic path, so reducing the efficiency of detection, see Section 9.2.6. When surveying for fish close to the surface a towed transducer must be used to look upwards. It is then the ventral surface of fish which is insonified by the acoustic beam instead of the dorsal surface; in some species this may mean a lower target strength.

9.4.2 Near Bottom Zone

The first factor to be established when considering errors due to the lack of coverage near the bottom is the closest point to the bottom at which detection/estimation

Figure 85



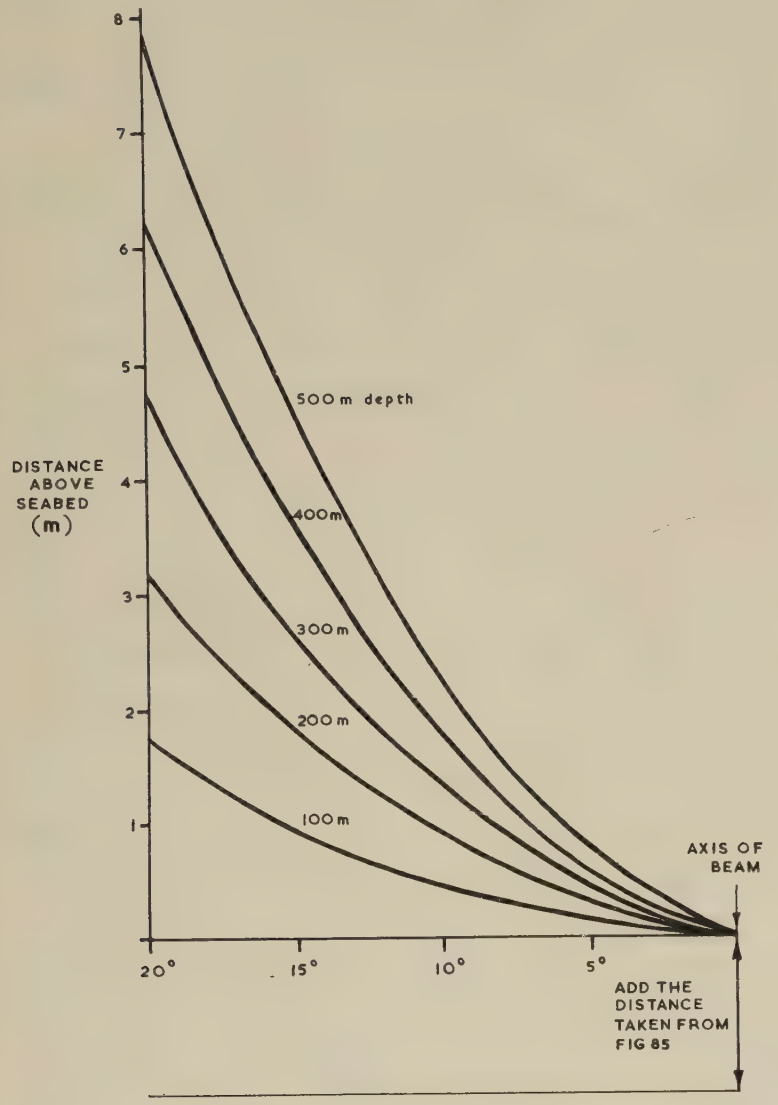
of fish is possible. The distance of this point above the bottom is half the physical length of the transmitted pulse $c\tau$, where c is the speed of acoustic waves in the water medium and τ is the time duration of the pulse. A graph of detection height on the axis of the beam above the sea bottom, in relation to pulse duration is shown in Figure 85.

The reason why this distance is half the pulse length is illustrated in Figure 18, where the lower of the two objects x-y (representing fish) may be considered as the sea bottom for the purpose of explanation. When the distance between the fish and the bottom is equal to half the pulse length, it is evident that, as the rear of the pulse leaves the fish, but is still moving towards the bottom, its echo starts moving toward the transducer. However, the leading edge of the pulse (or wavefront) has already been to the bottom and its echo has travelled by half the pulse length, also back towards the transducer. Therefore, at the instant we are considering, the front edge of the bottom echo is level with the rear edge of the transmitted pulse at the position the rear edge of the fish echo has just left. If the fish is any closer to the bottom than half the pulse length, the rear edge of the pulse would not have left the fish before the wavefront of the bottom echo arrived back at the fish position. The fish and the bottom echoes would therefore be merged.

A half pulse length is the theoretical distance for the discrimination between objects/targets, but in practice it may be greater because pulses are rarely perfect, taking a finite time to rise and decay. Instead of simply assuming a value of $c\tau/2$ from nominal figures for the speed of acoustic waves and the manufacturer's pulse duration it is instructive and sometimes important to measure these factors.

The speed of acoustic waves can be obtained from Figure 8, if the water temperature and salinity are known. This speed should then be multiplied by the measured time duration of the transmitter pulse, from the point where it first reaches 10% of maximum

pulse amplitude to where it has decayed to the 10% level. Speed is in metres/second and time in seconds, eg c = 1495 m/s and if $\tau = 0.5 \times 10^{-3}$ seconds, so $c\tau/2 = 1495 \times 0.5 \times 10^{-3}/2 = 0.374$ metres.



If the speed and time measurements cannot be made, c should be assumed to be 1500 m/s, τ taken from the manufacturer's data and the product of the two divided by 1.5 instead of 2 to allow for an imperfect shape.

Of course these figures for minimum distance refer only to the axis of the beam and, because of the spherically shaped wavefront of the pulse, the distances off axis are much greater, see Figure 86.

Figure 86

The minimum distance (height), at which fish can be detected, for beam angles relative to the axis and for given transmitter pulse lengths, can be calculated from

$$h = d(1 - \cos\Theta/2) + c\tau/2$$

where h = height in metres

d = total depth of water from transducer face to sea bottom

Θ = full beam angle of transducer at half power points

$c\tau/2$ = half pulse length.

Because detection ceases at $c\tau/2$ on the axis, all other detection along the wavefront ceases at the same time, thus the total volume where fish cannot be detected, the dead zone, may be considerable, Mitson (1982).

The volume of the 'dead-zone' when related to a conical beam, comprises the frustrum of a cone minus the cap of a sphere. In terms of the depth of water from transducer to bottom (d), beam angle Θ and the pulse length $c\tau$ it can be expressed as

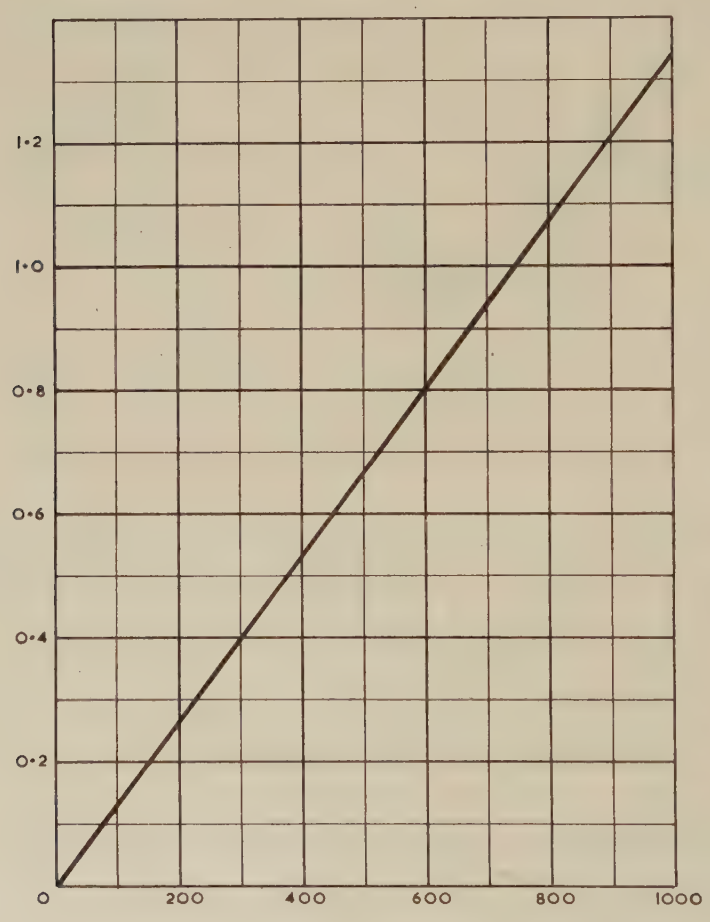
Volume of dead zone = Volume of frustrum - Volume of cap

$$V_{frustrum} = 0.268\ (d - c\tau/2)((1 - \sin\Theta/2)/\tan\Theta/2) + c\tau/2\ [(2d \tan \Theta/2)^2 + 2((d - c\tau/2)\ \sin\Theta/2)^2 + (2d \tan\Theta/2)(2[d - c\tau/2]\sin\Theta/2) \quad \ldots\ldots\ (83)$$

$$V_{cap} = \pi/3[(d - c\tau/2)((1-\sin\Theta/2)/\tan\Theta/2)]^2\ [3(d - c\tau/2)-(d-c\tau/2)\ ((1-\sin\Theta/2)/\tan\Theta/2)] \quad \ldots\ldots\ (84)$$

The volume given above for the dead zone relates to one transmission only, whereas in normal survey operation a succession of transmissions occur as the vessel moves along its course. Depending on the beam angle, the speed of the vessel and the depth of water, these transmissions may overlap, especially near the sea bed. These factors therefore, cause some variability in the effective sampled volume of the region where the pulse approaches the height $c\tau/2$ above sea bed. But, whatever the beam angle, the depth of water, or the rate of transmission, the distance of $c\tau/2$ above the sea bed marks a definite boundary under which no sampling is possible at all.

Figure 87



For each km^2 of survey area, the total volume of water near the sea bed which cannot be sampled is $10^6 c\tau/2$ (m^3) shown in Figure 87 for pulse durations of 0 to 1.2 ms. This clearly emphasises the need for the shortest possible pulse duration in order to minimise this zone which could be designated the definite dead zone (DDZ).

In certain circumstances it may be important to consider the volume of the beam as the pulse approaches the bottom, especially if the near bottom sample is important. The acoustic pulse increases in volume as it progresses in depth, but it reduces sharply as the half pulse length height above the seabed is approached.

Whilst the transmitted pulse contained in a conical beam is travelling through the sea, clear of any boundaries, its volume is contained within a spherical shell of common solid angle between the ranges d_2 to d_1 where $d_1 - d_2$ is equal to the pulse length $c\tau$.

This volume can be calculated from

$$V_1 = (2\pi/3)(1 - \cos\Theta/2)(d_1^3 - d_2^3) \quad \ldots\ldots\ (85)$$

where V_1 = the volume of the range shell in m^3

d_1 = depth from transducer to the pulse wavefront (m)

d_2 = depth from transducer to the rear of the pulse (m)

$\Theta/2$ = half angle of the beam in degrees, to the half power level

At the point where the wavefront is one pulse length above the seabed, the volume in which detection can be made is reduced to

$$V_2 = (\pi/3)(1 - \cos\Theta/2)(d_1^3 - d_2^3) \quad \ldots\ldots\ (86)$$

where the units have the same dimensions as above.

As the wavefront travels through the last half pulse length to reach the distance $c\tau/2$ above the seabed, the volume diminishes to the cap of a sphere, which finally reduces to zero at the height of $c\tau/2$. For this situation the 'cap' is on the axis of the beam and the minimum useful volume for sampling purposes might be considered as that occurring when the height of arc of the cap is slightly greater than the dorsivental height of a single fish on the beam axis.

Volume of the cap of a sphere, V_3 (m^3).

$$V_3 = \left((\pi h_1^2)/3\right)\left[3\, d_1 - h_1\right] \quad \ldots\ldots\ (87)$$

where h_1 = height of the arc (m)

d_1 = depth of water from transducer to the bottom of the arc (m).

The simple treatment given above when studied in conjunction with the Figures should be sufficient for the organiser of an acoustic survey to make an analysis of the volumes of water he is able to sample and those which he is not.

9.4.3 Inaccessible Fish Distribution

Section 9.4.1/2 discussed the situations when the coverage is limited by the pulse length of the echo-sounder and the roughness of sea surface or bottom. A more difficult situation to assess and make allowance for, is when a proportion of the fish population moves into water so shallow, that the combination of draught of the vessel, the minimum distance from the transducer, and the depth restriction of $c\tau/2$ leave little, or no water to be surveyed.

In such circumstances a little inshore vessel is needed, preferably with a quiet engine, to carry a suitably small calibrated echo-sounder and tow a transducer as close to the surface as possible. The Simrad EY-M, plus a tape recorder, is suitable for this

purpose although it works at 70 kHz and care must be taken in relating the results to higher or lower frequencies. Results can be processed through a QM integrator by means of the interface described by Larsen (1983).

9.5 Vessel Avoidance (variability with depth of fish)

It is necessary for the survey operator to be aware of fish behaviour in relation to the survey vessel for this may cause an incorrect estimate of the stock to be made. Fish react to both acoustic and visual stimulii, but the degree of reaction varies with species, season, time of day (probably related to feeding), intensity of the disturbing source and the acoustic frequency band. Some pelagic fish are known to move from areas where the large number of vessels must be producing considerable amounts of low frequency noise.

There are two effects to be considered. Fish moving out of the path of the vessel completely and fish swimming downwards, but remaining in the path of the acoustic beam. If fish move out of the path, the situation is serious, so what can be done? It is rarely possible to modify the vessel so as to reduce the noise level significantly. The measures necessary to decouple the low frequency noise produced by diesel engines are very costly, even if introduced during the building of the vessel. It may be possible to find periods when the particular species is less sensitive to noise, for there is evidence to show considerable variability with time of day and season.

Recordings have been made showing that it is not only fish concentrations very close to the surface which are affected by a ships presence or the noise it generates. Concentrations of adult herring, under the path of the vessel, extending from about 10 m below the surface down to 40 m, have completely disappeared, but quickly returned again after its passage, Olsen (1979). The fact that fish were densely packed from top to bottom of the school may have led to the 'scare' reaction passing quickly through it. It is possible that the noise intensity from the particular vessel was very high, thus causing such an extreme reaction through the water column, but noise level data on this vessel are not available.

To guard against the possibility of survey results being affected by this type of behaviour in relation to his vessel, the acoustic survey operator is advised to make observations whenever possible which may assist him in determining the extent of the problem, or even if it exists at all. Occasionally visual observations can be made, but can be misleading because fish very close to the surface and in the path of the vessel will move aside. A horizontally directed sonar beam may provide useful clues by showing the general distribution of fish in the area which can be related to the quantities being recorded by the echo-sounder.

Sometimes it is possible to observe the rapid descent of fish under a vessel if a wide beam transducer is in use. Normally a fish at constant depth relative to the transducer will produce an inverted 'V' shaped trace if the axis of the beam crosses it, but, a quick descent will appear as a sloping line on the paper record. This type of movement produces a change in the orientation of the fish with respect to the acoustic beam, hence its effective target strength changes, almost certainly becoming lower. If

such behaviour is widespread amongst the fish population being investigated, then the overall stock estimate will be biassed low. Avoidance behaviour is likely to be more prevalent in shallow waters because the vessel noise does not die away quickly, but reverberates between surface and bottom.

The use of towed transducers may be a good solution under some conditions, if they can be towed well clear of the ship and are not likely to be visible to the fish being surveyed. They also have other advantages, see Sections 9.3.4, 9.3.5, 9.6.1.

9.6 Other Errors

There are other possible sources of error to be considered. The first two relate to operational matters and the last two to the biomass being surveyed.

9.6.1 Motion Induced Errors

Conditions for acoustic survey are most satisfactory when the transducer beam axis remains approximately perpendicular (at an angle of 90°) to the sea bottom, or oscillates slightly around this position.

It is difficult to quantify the exact effects of roll and pitch motions of a vessel in relation to the schools of fish it is surveying - the greater the amplitude of motion and the narrower the beam, the more significant the error becomes. Stanton (1982) has studied the problem and his paper is recommended to those using hull-mounted transducers.

When the rate and amplitude of motion is high and the fish are fairly deep a transmission made at one instant of time may occur at the extreme roll of the vessel and by the time that echoes start to return, the transducer may be 'looking' in another direction. This effect is significant when narrow beam transducers are used in a vessel which has a high rate of movement in pitch or roll. Consider a maximum roll amplitude of ±15°, at a rate of 5°/s for a vessel fitted with a transducer having a full beam angle of 15°. It is clear that at either extreme of the roll, the transducer beam will be 'looking' away from the vertical, and near bottom detection will be affected because of the rapid changes in range as the beam swings. There will be a reduction in echo amplitude due to the outer edges of the beam (low intensity/sensitivity) being at the shortest range to the bottom. Both of these effects give rise to a 'ragged' bottom echo, making it difficult for any automatic 'bottom stop' or 'bottom lock' to function efficiently, or for fish to be discriminated from the bottom echoes. There would not be a complete loss of signal for the angle of beam and the rate and angle of motion, given above at practical ranges for fish detection, due to the effect of motion alone. Acoustic waves travel at about 1500 m/s, so if we assume a maximum range/depth of 375 m, the time for a pulse to travel to that range and an echo to travel back, would be 0.5 s. During this time the beam would have moved 2.5°, not sufficient to cause a serious loss of signal.

Because many species of fish have directional scattering characteristics, where the main 'lobe' of the response is not necessarily perpendicular to the length axis of the fish's body there may be an effect when the transducer is 'viewing' these responses as

its angle changes due to motion. Directional effects of fish target strength response greatly increase at higher frequencies and a fish of 40 cm length at 38 kHz might have a response 5° wide, which at 120 kHz would be reduced to about 1.5°. Possibly the random angles of maximum fish response and transducer motion tend to give insignificant errors.

9.6.2 Acoustic Beam Overlap

The amount of overlap will vary according to the beamwidth in the fore-aft plane, the rate at which transmissions are being made, the speed of the vessel and the depth interval at which integration is taking place. Each of these parameters has to be taken into account in the calculations.

9.6.3 Shadowing Effects

A problem which is difficult to quantify arises when the density of fish in schools is such that those in the lower levels of the school are in the 'shadow' of the top layers. As a result the acoustic echo signals may not be proportional to fish density, the normal premise for echo-integration. This effect has been studied theoretically and using practical data by Ertugrul and Smith (1982). Other useful references are Røttingen (1976), Foote (1978, 1978a, 1978b), and Lytle and Maxwell (1982).

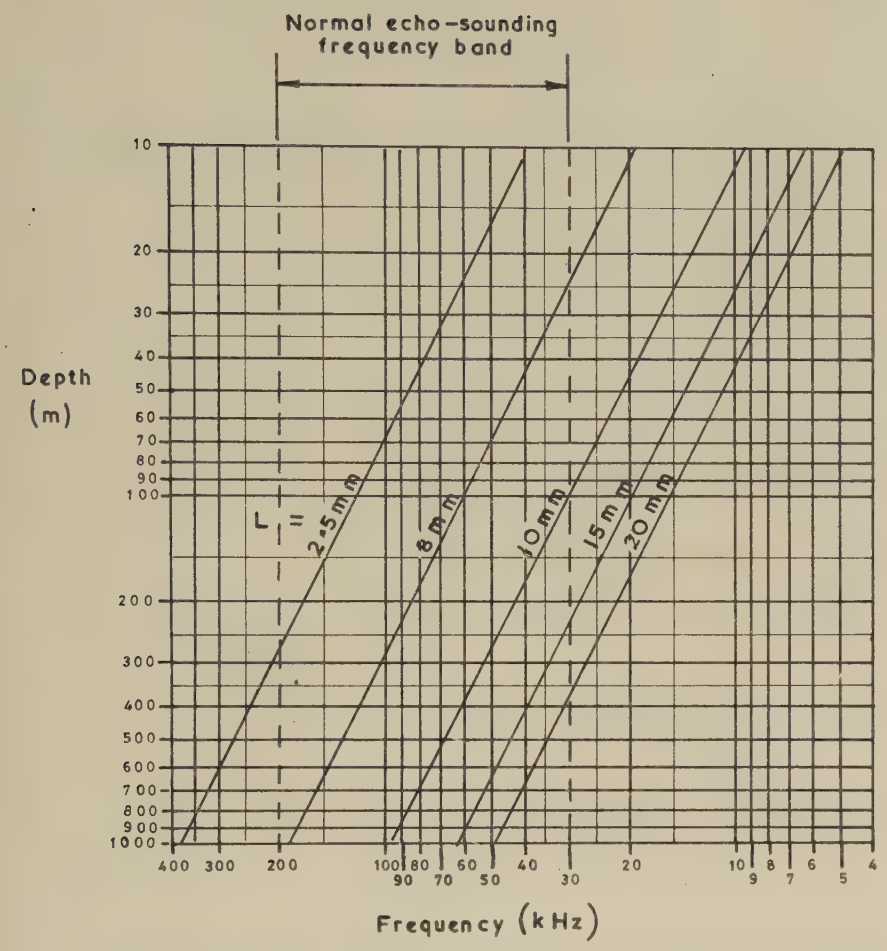
9.6.4 Resonance of Organisms

Air bubbles appear within biological organisms over a wide size range, from fish larvae to the swimbladders of adult fish, and they have been studied in relation to resonance. When an acoustic wave strikes a bubble, the latter responds to the compressions and rarefactions of the wave. At resonance the frequency of the wave and size of the bubble interact in such a way that the bubble compressions and rarefactions are a maximum, ie its oscillations are at their greatest. Thus a maximum of energy is extracted from the acoustic wave. Some of the energy is scattered in all directions by the pulsating bubble, the remainder being changed to other forms of energy such as heat.

Various effects prevent swimbladders from acting as ideal resonators, the most important being the viscous damping due to the surrounding flesh and tissue. A detailed description of the physical process is beyond the scope of this manual but it must be realised that the phenomenon of resonance can be of considerable importance in fisheries acoustics, for it can give rise to an enhanced target strength.

There are two components of resonance to be considered.

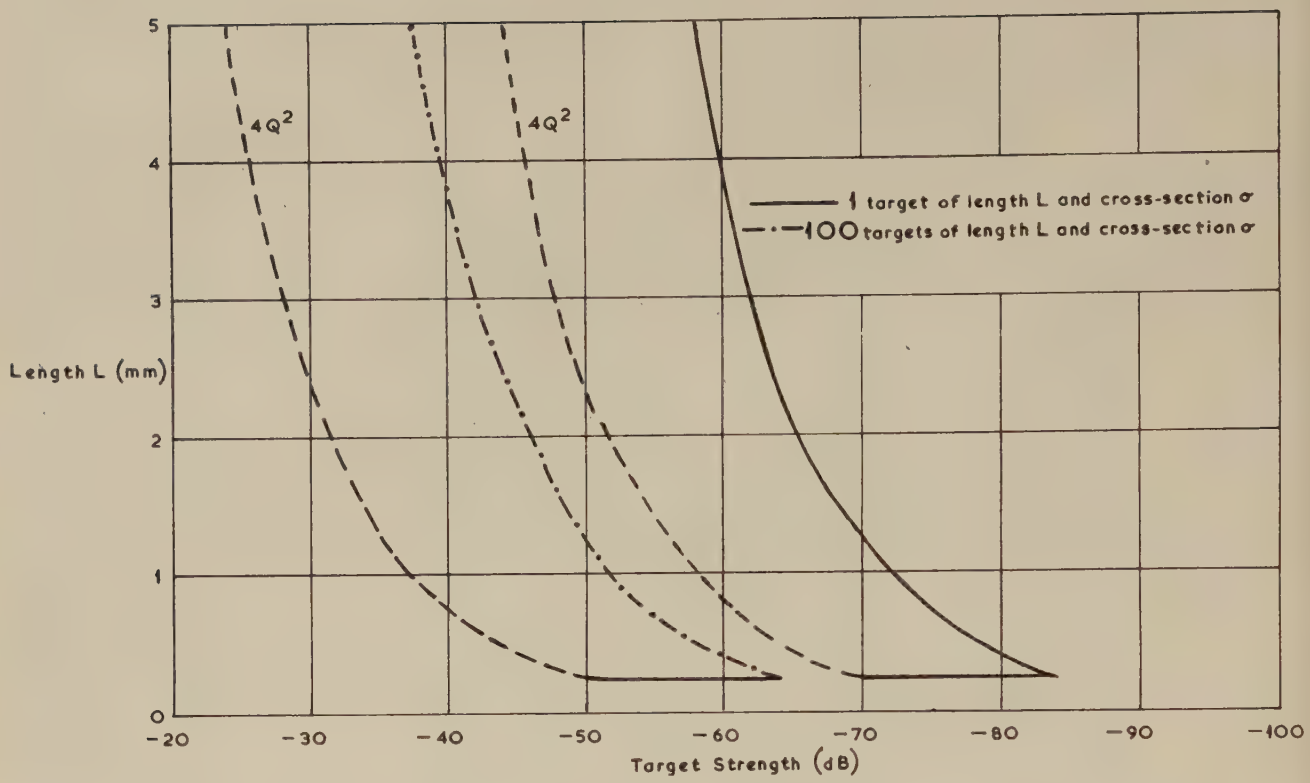
Figure 88



1. Frequency: which depends on the size of the swimbladder, and the depth of the fish, Figure 88.
2. The 'Q': This factor determines the increase in back-scattered energy over that due to the geometric cross section of the target. 'Q' is the reciprocal of the damping factor, which represents the sum of the effects limiting the oscillation.

At resonance an ideal bubble would have a ratio of acoustic cross-section to geometric-cross-section of $4Q^2$. Measurements on large fish, such as cod and saithe have shown Q to be about 2.5, but it is possible that smaller organisms may have higher Q's for the damping factor was thought to be due principally to shear losses within the tissue of the swimbladder wall. Even with a Q = 2.5 the ratio of acoustic cross-section to geometric cross-section is increased by 25 times (14 dB). The effect of this is shown in Figure 89 where the target strength of one organism 5 mm in length is seen to increase

Figure 89



by this amount and 100 organisms of the same size could evidently reach a TS of -24 dB, comparable to a very large fish. A layer of such organisms at about 40 m depth might give a significant result on the echo-integrator used at 38 kHz. Because of enhanced TS of such organisms it may be difficult to discriminate between densely aggregated resonant targets and densely schooled non-resonant fish.

10. DATA ANALYSIS FOR FISH ABUNDANCE ESTIMATION

10.1 Data Handling and Processing

Echo-integrator surveys generate large amounts of data which must be manually reduced if in analog form, or by computer if it is digital. These data may be processed during the course of the survey if the research vessel has sufficient space and is suitably equipped. If this is not possible the data must be stored carefully for processing on shore later.

The quality of these data depends partly on care in their collection so it is particularly important that the following points are strictly monitored.

a. Ensuring that data entry on acoustic log sheets is consistent and correct
b. Checking that instrument controls are properly monitored by all scientific personnel (observers) responsible for the acoustic watches
c. Correcting for 'drift' in the integrator, see 9.2.5 a phenomenon specific to the analog design of circuits, and to correct for factors such as: 'bottom pulse failure', see 9.2.1; 'layer selector spike', see 9.2.2; 'secondary echo interference', see 9.2.4 and 'blocking of integration due to a school generated bottom pulse' see 9.2.3
d. Eliminating false echo integrals attributed to various sources of noise, plankton layers and/or other scattering entities that may interfere in the measurements.

Whilst (a) and (b), can be considered self-explanatory and straightforward, (c) is rather complicated. A detailed description of the possible errors under (c) and some corrective measures for them are given in section 9.2. As for (d) this involves a comparison of echograms and integrams as explained in 10.1.1.

Chapter 10 deals only with post-survey, shore-based processing of analog data. Figure 90 shows the main elements in the system for processing analog integrator data. Satisfactory data processing and the derivation of absolute fish abundance estimates also depend to some extent upon the observer's subjective interpretation of the various displays as well as his ability to relate the measurements obtained to complementary biological samples. This involves a complex human decision making process, directly influencing the final abundance estimate as inferred from Figure 90. The quality of these decisions is necessarily dependent upon the observer's skill and experience in the interpretation of the acoustic data displays.

The nature of survey data are such as to make it imperative that they first be studied and verified. Both echo-sounder records, integrams and log sheets are also subjected to careful scrutiny.

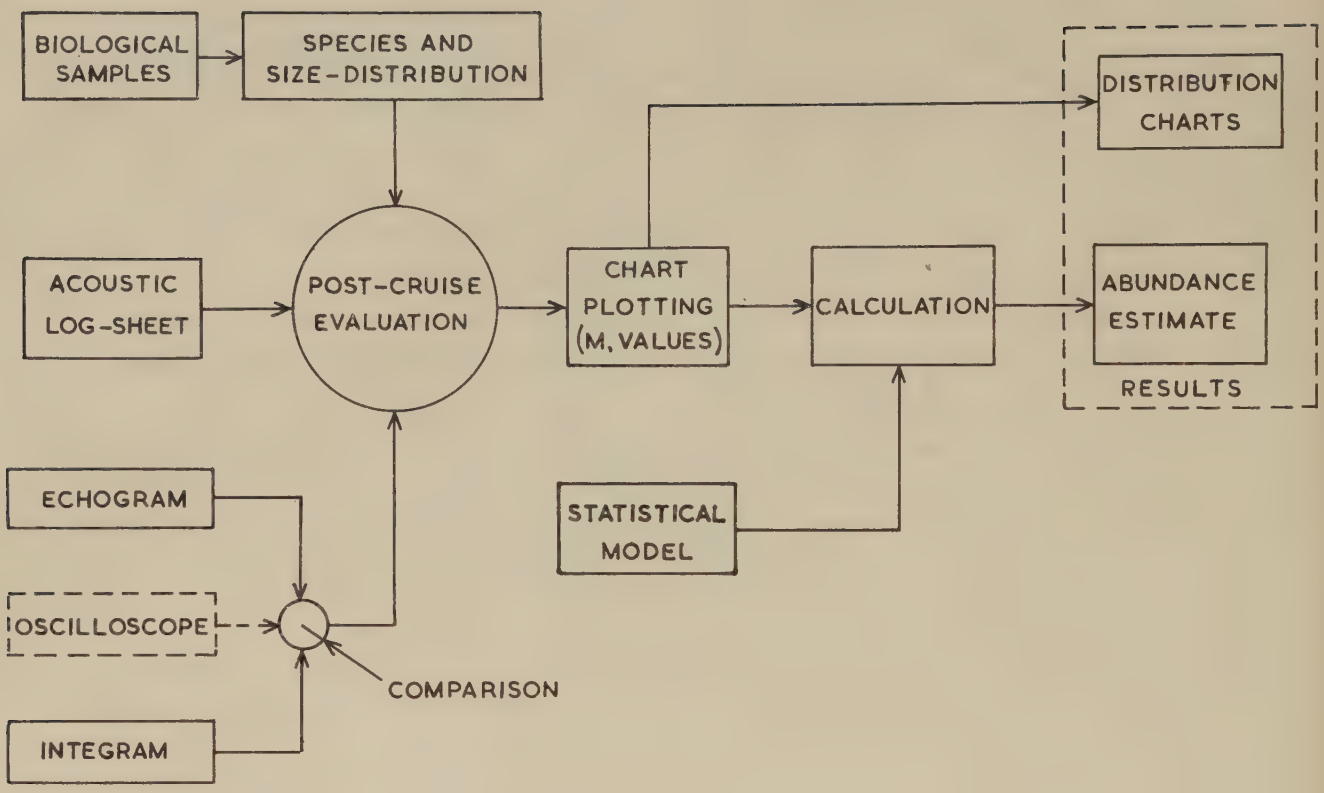


Figure 90 Outline of system for data handling and processing

10.1.1 Visual Evaluation

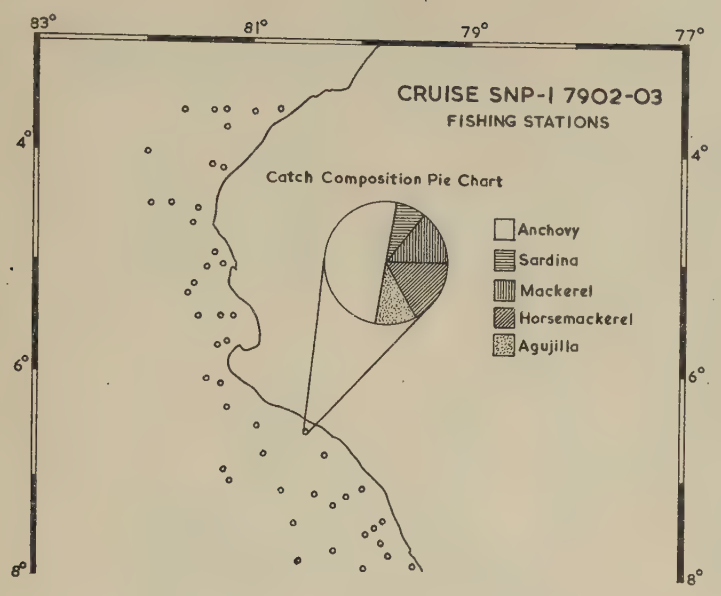
The purpose of this type of evaluation is twofold,

i) to carry out corrections for possible errors under (d) as defined above and,

ii) to compare fish trace characteristics with the graphic integrator output (which represents a direct density index) in order to separate recorded biomass into discrete species and/or into plankton and fish.

In practice the most efficient way of comparing the two displays is to spread the echograms/integrams side-by-side (e.g. on a long table) so that 10-20 nautical miles of a transect can be viewed simultaneously. The advantage of such an over-view is that it often permits the detection of specific and important trends in data that might otherwise escape observance. Such trends can, for example, relate to a gradual appearance of a plankton layer which at some point will become mixed with the fish layer or schools of interest. In this case, careful examination of the long distance changes in trace characteristics, and correlation with the slope of the integrator output graph, often makes it possible to introduce reasonably accurate corrections. A similar approach also applies to other phenomena like secondary bottom-echo interference and even sea-surface noise which may have gradually built up to interfere significantly with the acoustic measurements.

Figure 91



The second purpose of the visual evaluation is to compare the acoustic displays with the related catch samples, e.g. in the form shown in Figure 91 (from Jóhannesson and Vilchez, 1979). Experience gained in many FAO projects demonstrates that such a comparison can significantly assist in the process of assigning echo-integrator values to a particular fish species. This can help to delineate their individual geographic distribution in areas where catch samples are scarce or simply not available.

10.1.2 Mapping and Representation

A successful completion of the first two stages of data analysis described above, will result in a 'clean' set of integrator values (M), i.e. a clearer interpretation in terms of fish species and quantities. The third stage is to plot the M values. For an analog integrator the relationship between the M values and each survey sample represents a quantity defined by two coordinates relative to the water surface (latitude and longitude) and one scalar property, that is, the M-value, in millimetres, for example. A multi-channel integrator also offers a third coordinate, the depth.

A typical chart showing an actual track pattern from a large-scale survey together with the plotted M values is presented in Figure 92. With the survey data processed in this form, subsequent analysis normally proceeds along two lines, i.e. one aimed at data presentation and the other to derive absolute abundance estimates as shown schematically in Figure 90.

The purpose of data display and presentation is generally twofold; firstly to exhibit the survey results in a suitable form for the customer (e.g. fisheries managers). Secondly, to search for a better interpretation of data to realize their full potential which may significantly aid studies of trends and time-series, also correlation. With powerful mini-computers becoming commonplace, acoustic data display and presentation is rapidly developing in detail and sophistication.

Figure 92

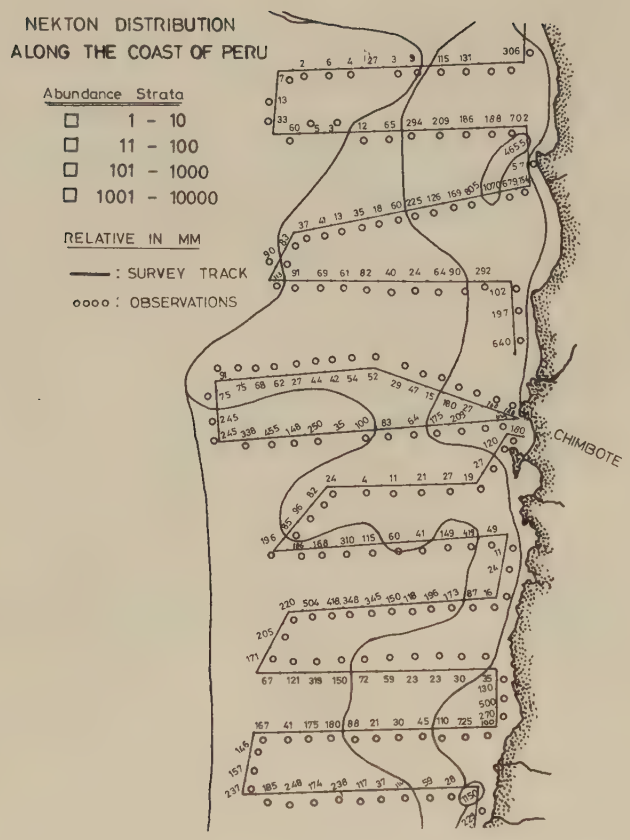
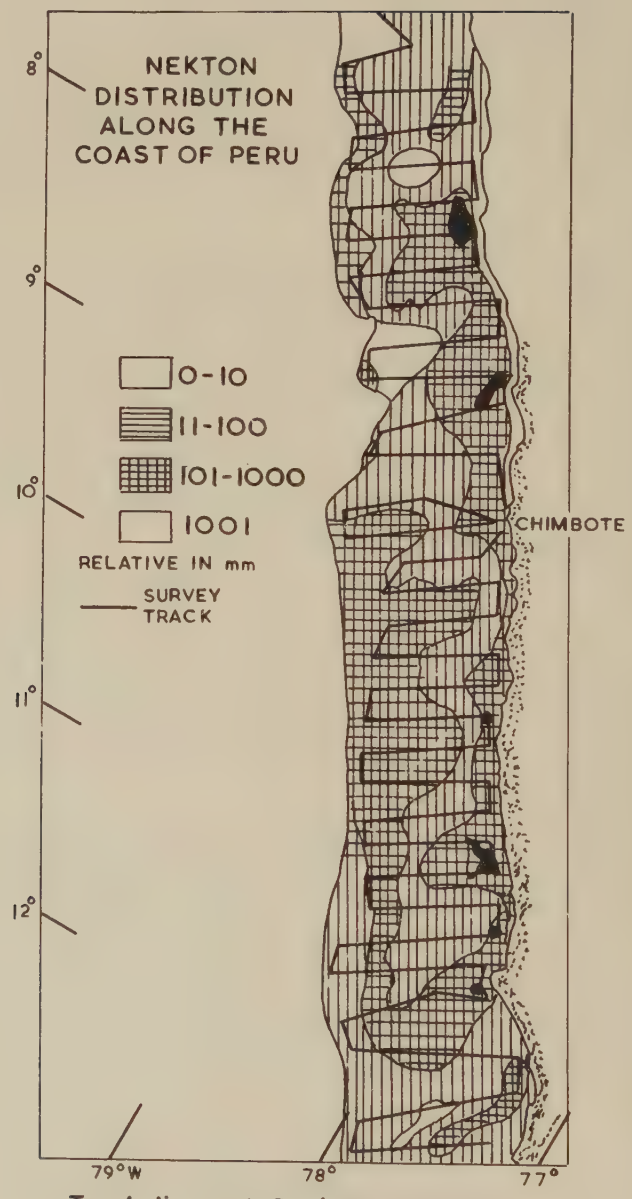


Figure 93



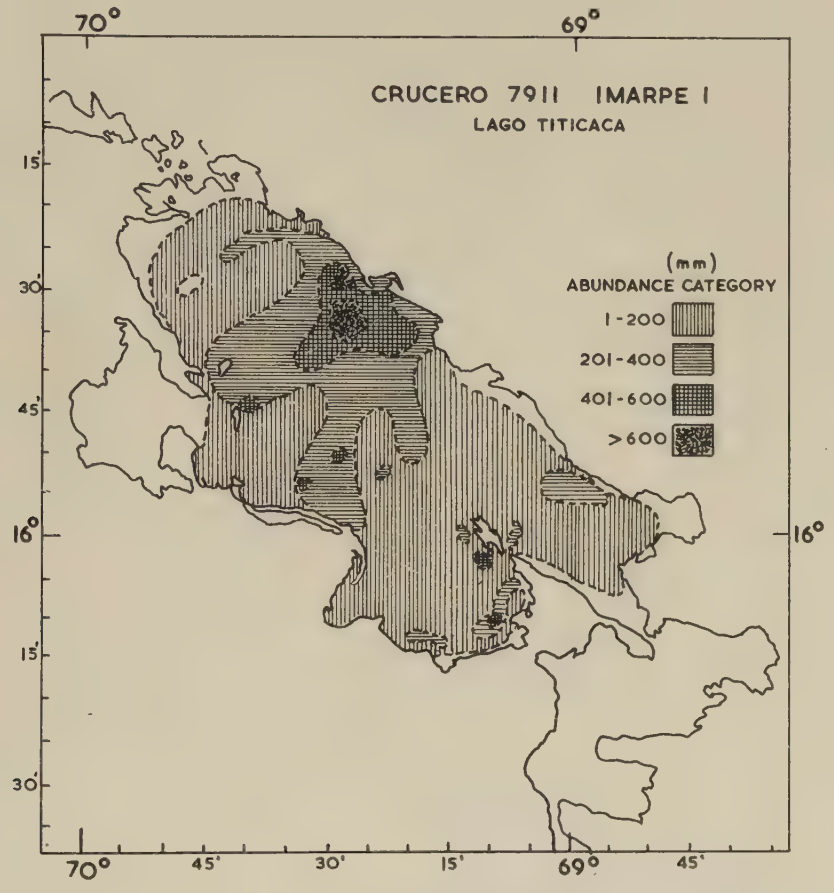
Track lines of Cruise No 7603
Biomass contour lines drawn manually

For an illustration of this subject a summary of typical data presentations, partly reflecting the evolutionary changes over the past years is presented below.

A. Biomass distribution charts

i) Geographic Maps: Perhaps the most common way of mapping at present is shown in Figures 93 and 94. The first figure relates to a large volume pelagic stock along the coast of Peru, whilst the second one maps a relatively dispersed lake population. The difference in levels of the relative abundance categories should be noted but, otherwise the figures are self-explanatory.

Figure 94



The geographic distribution of fish in Lake Titicaca estimated on the basis of 4 density categories

ii) Bar Graphs: These are also a fairly common form for data presentation. Figure 95 presents the same data as in Figure 94 but now in the form of a bar-graph. Such graphs, in a different fashion, can also be used to display biomass variations along a vessel's survey track-lines as illustrated in Figure 96 which is self-explanatory. A further construction of a bar-graph by a mini-computer facility is shown in Figure 97.

Figure 95

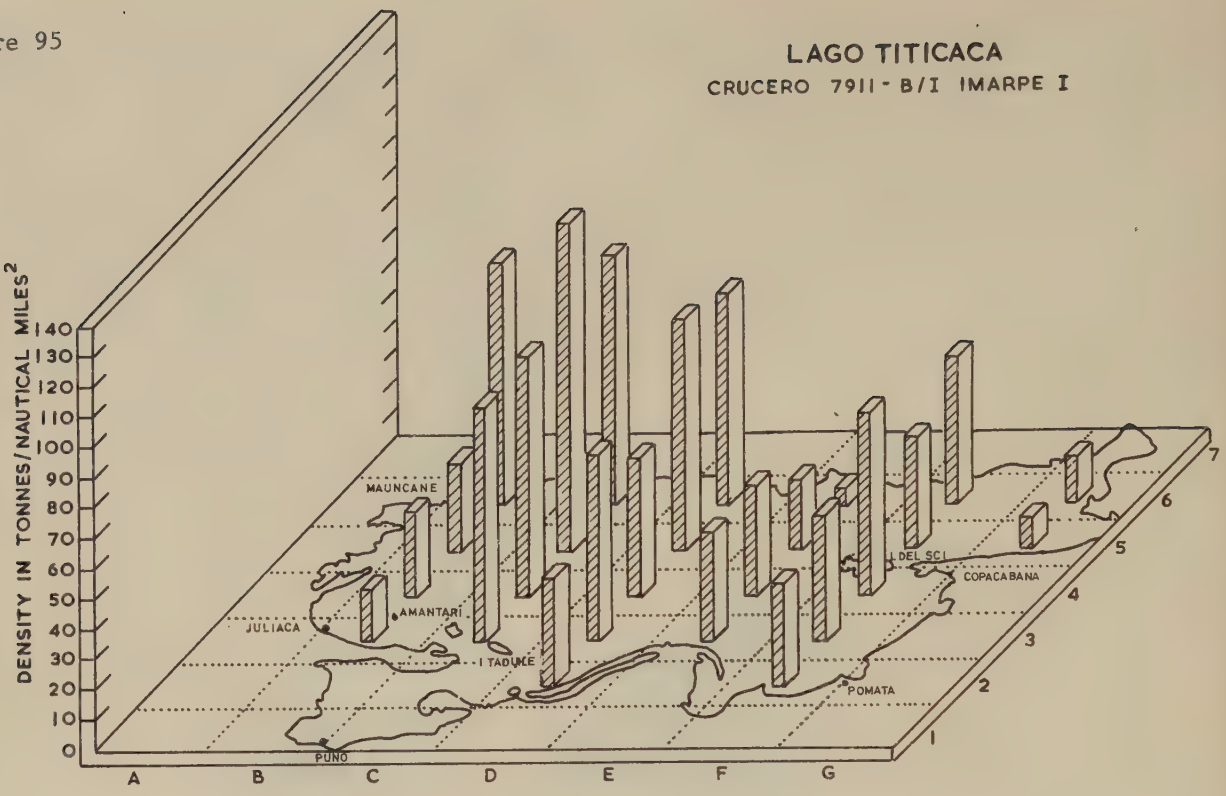
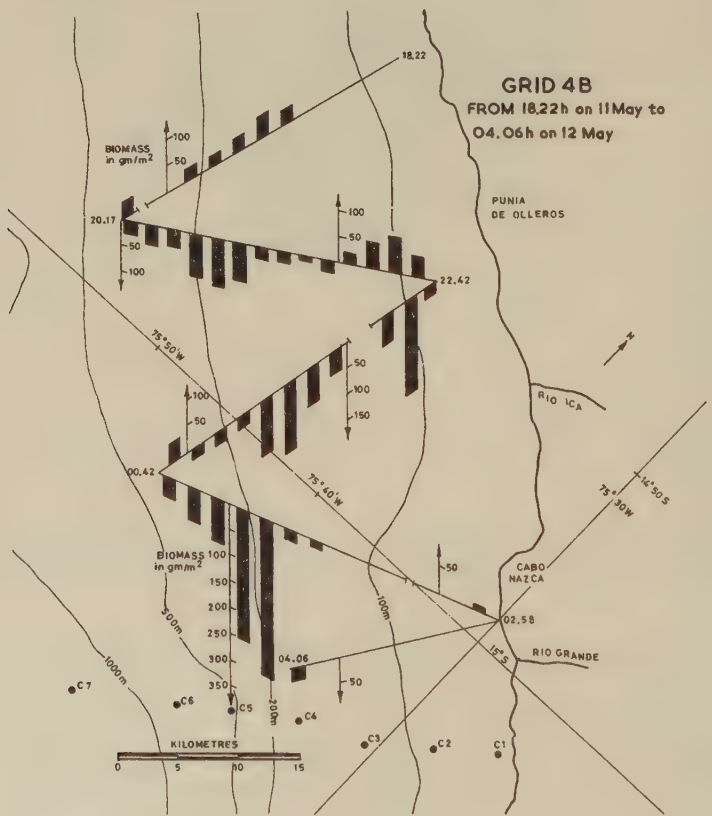
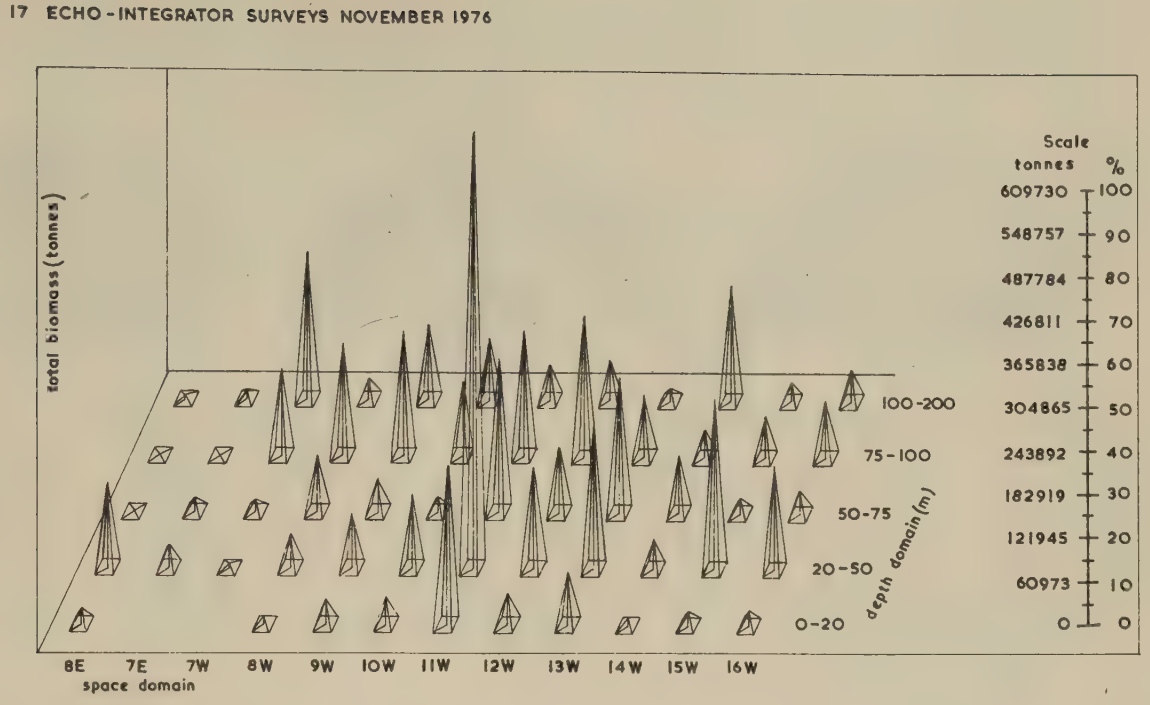


Figure 96



Distribution of nekton biomass in grid 4B during R/V THOMPSON, Leg 1, 1976. Local time is given at the end of each transect. Values under 10g/m^2 are not shown

Figure 97



iii) Three-dimensional representation: This type of computer plotting is shown in Figure 98 below and refers to part of the same data presented in the form of a geographical distribution map in Figure 93.

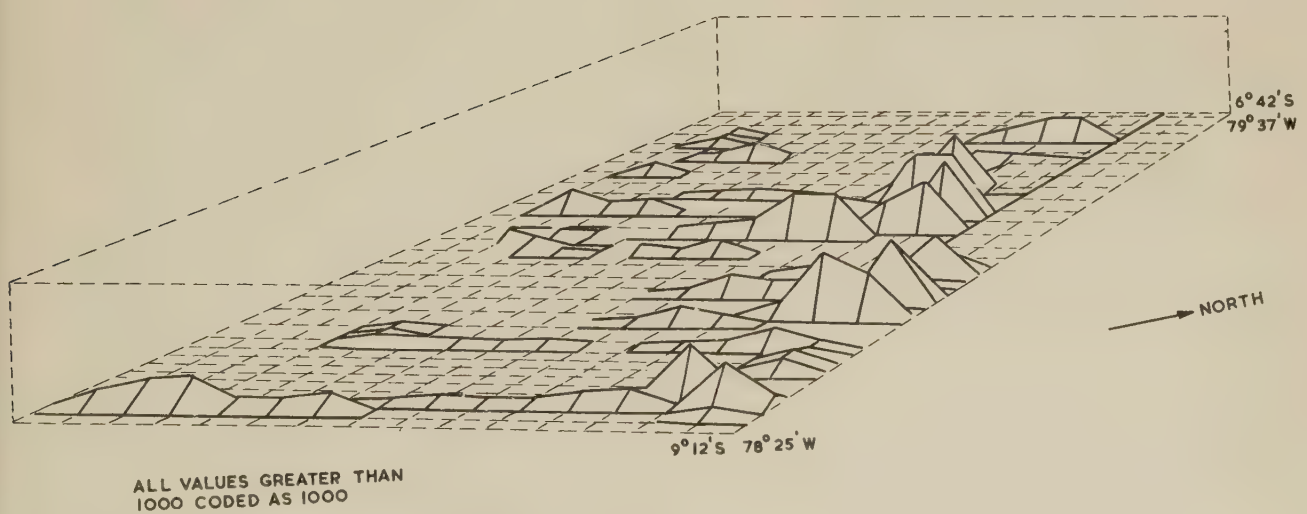


Figure 98 All integrated echo intensities censored above a value of 1000

A somewhat different three-dimensional plot is shown in Figure 99 below.

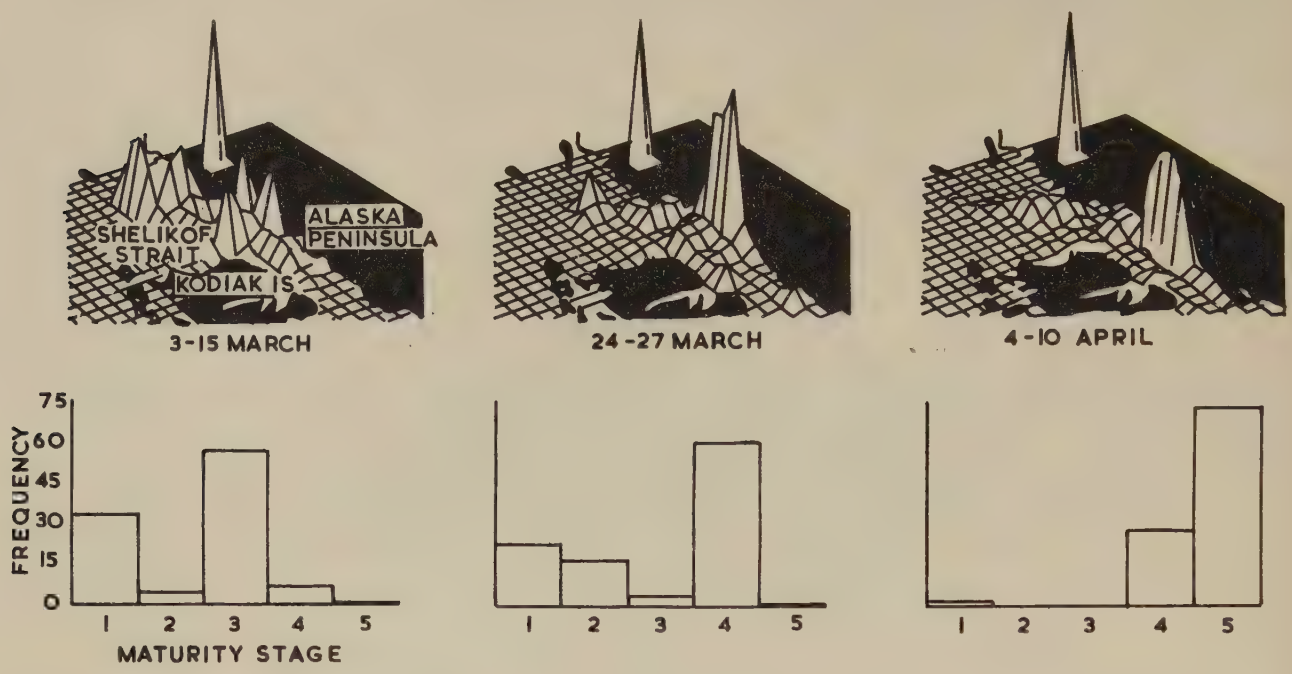


Figure 99 Relative density distribution and maturity composition (sexes combined) of off-bottom pollock during each of three acoustic surveys in 1981

B. Abundance profiles

i) Within-survey variability: An example of graphic analysis to study within-survey variations in echo-abundance by degree of latitude, as a function of the distance from the Peruvian coast, is shown in Figure 100 along-side.

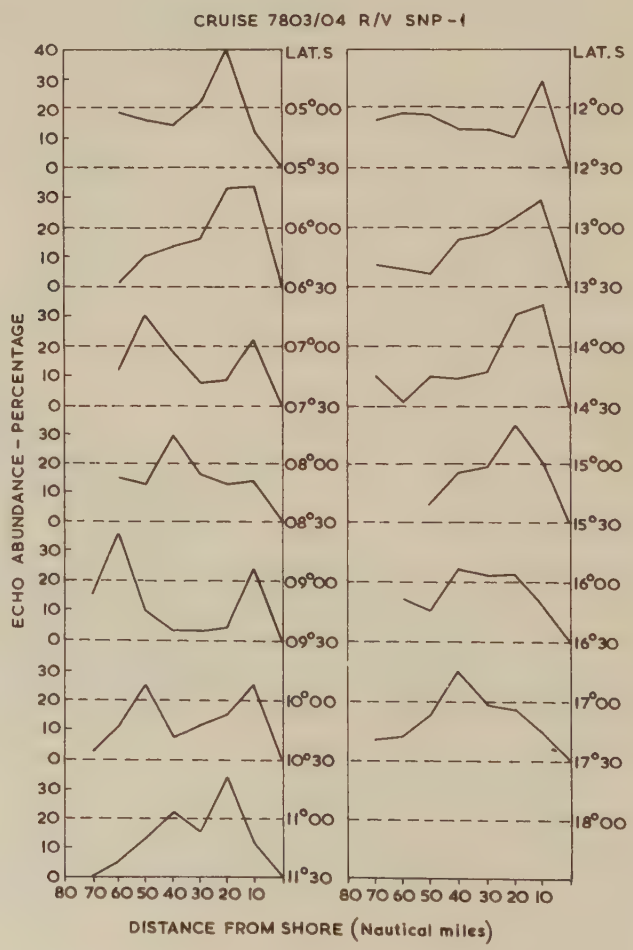
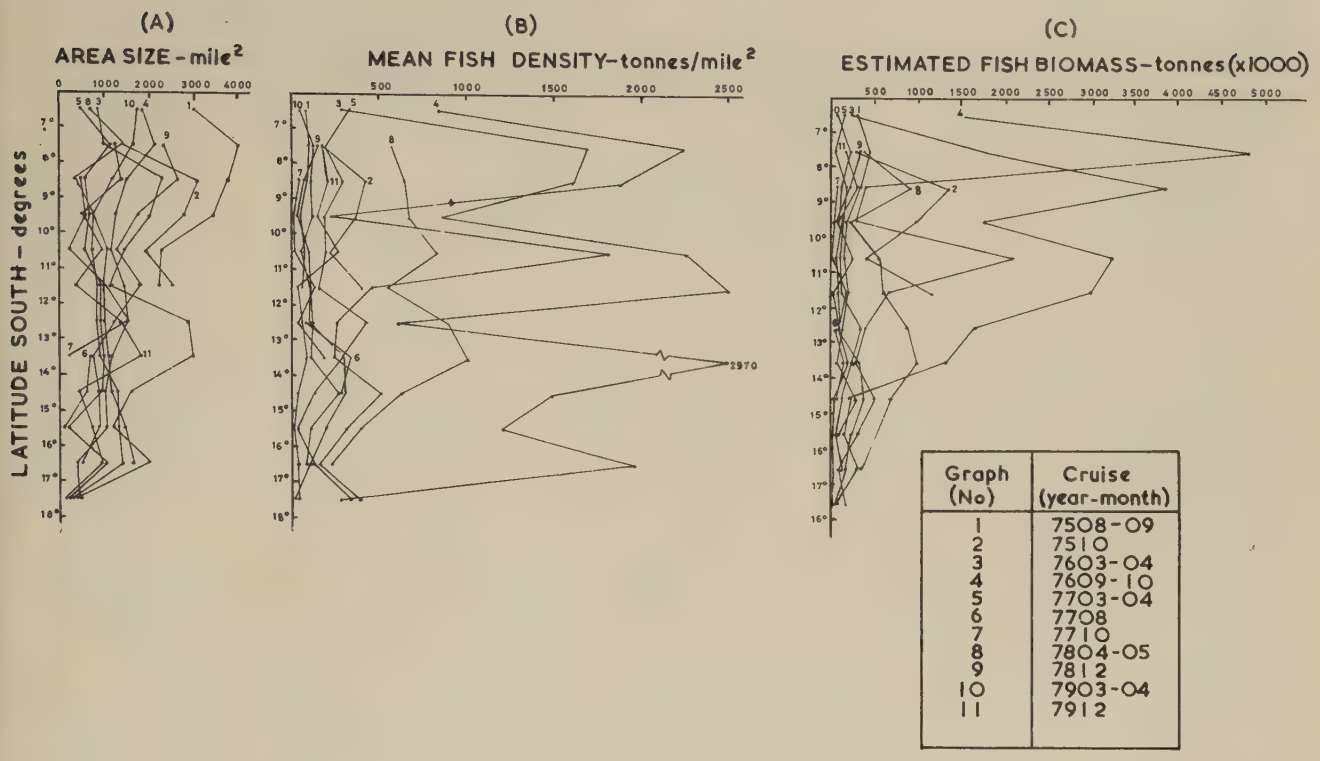


Figure 101 Distribution characteristics of Peruvian anchovy

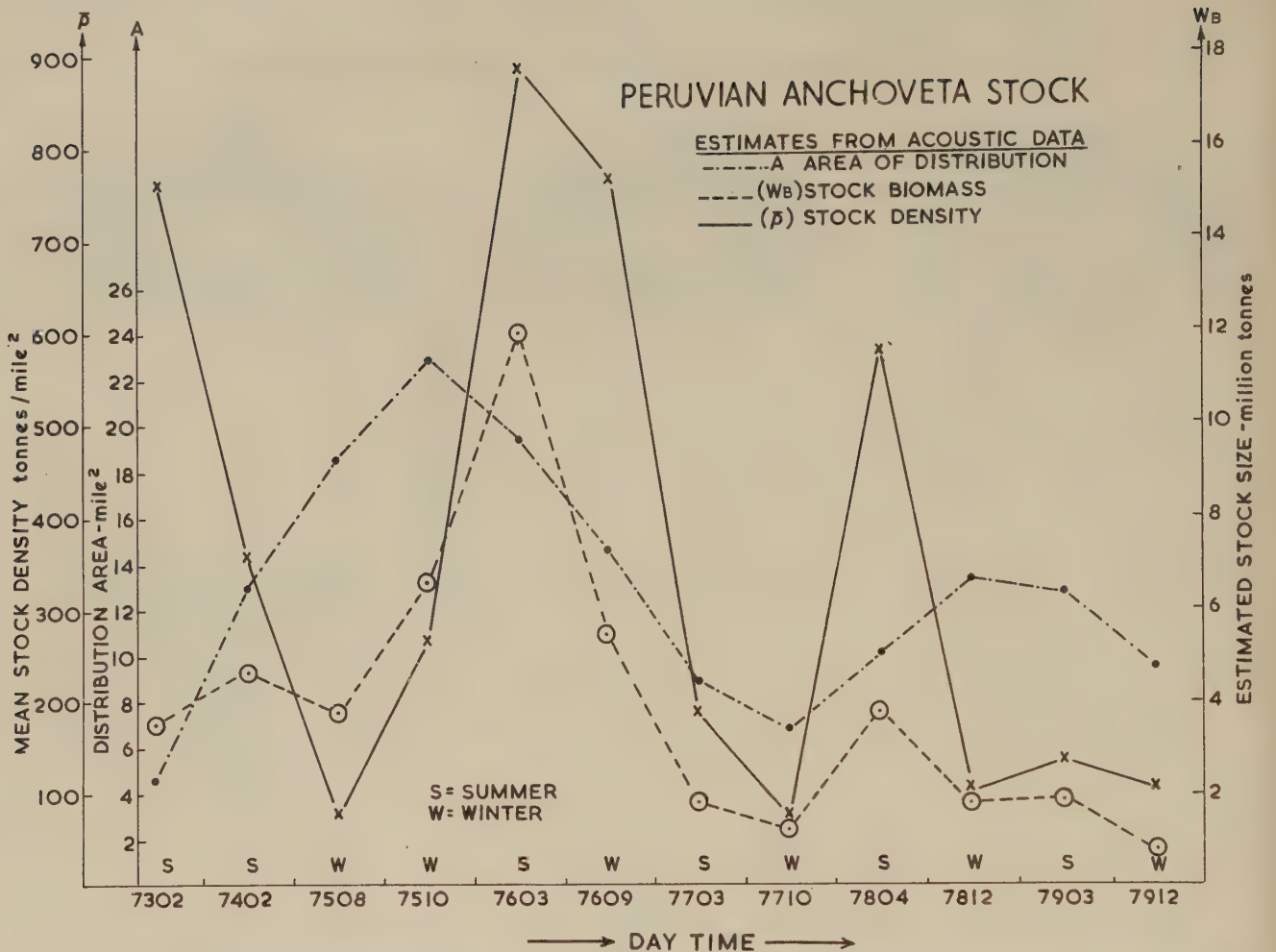


ii) Survey-to-survey comparisons: This type of data presentation is particularly useful to study the characteristics of the littoral distribution of large volume pelagic stocks. An example from the Peruvian anchovy stock is shown in Figure 101. Data from eleven survey cruises are individually graphed to facilitate comparison with results from one survey to another, conducted over a period of four years. The principal area/density/weight magnitudes of the surveys are portrayed separately, using units of averages per degree latitude as the variate. In this form data lends itself to visual examination to judge whether any stationary pattern exists. If so it could serve as a basis for a better statistical survey design, e.g. to define some natural strata and/or to adopt probabilistic sampling allocations. A further display of these data is in Figure 102 where the principal survey variates are graphed to study seasonal changes in the area/density/biomass relationships.

C. Diurnal Variability

In ten years or more of integrator surveys it has been noted that significant differences can occur in the night/day ratio of integrated echo intensities returned from the same stock in the same area. Hence, it is commonplace in today's surveys to examine the extent to which such differences may influence an estimate and how a statistical compensation can be applied. In this case also a graphic analysis can

Figure 102


PERUVIAN ANCHOVETA STOCK
ESTIMATES FROM ACOUSTIC DATA
A AREA OF DISTRIBUTION
(WB)STOCK BIOMASS
(p̄) STOCK DENSITY
MEAN STOCK DENSITY tonnes/mile²
DISTRIBUTION AREA-mile²
ESTIMATED STOCK SIZE-million tonnes
S= SUMMER
W= WINTER
S S W W S W S W S W S W
7302 7402 7508 7510 7603 7609 7703 7710 7804 7812 7903 7912
DAY TIME

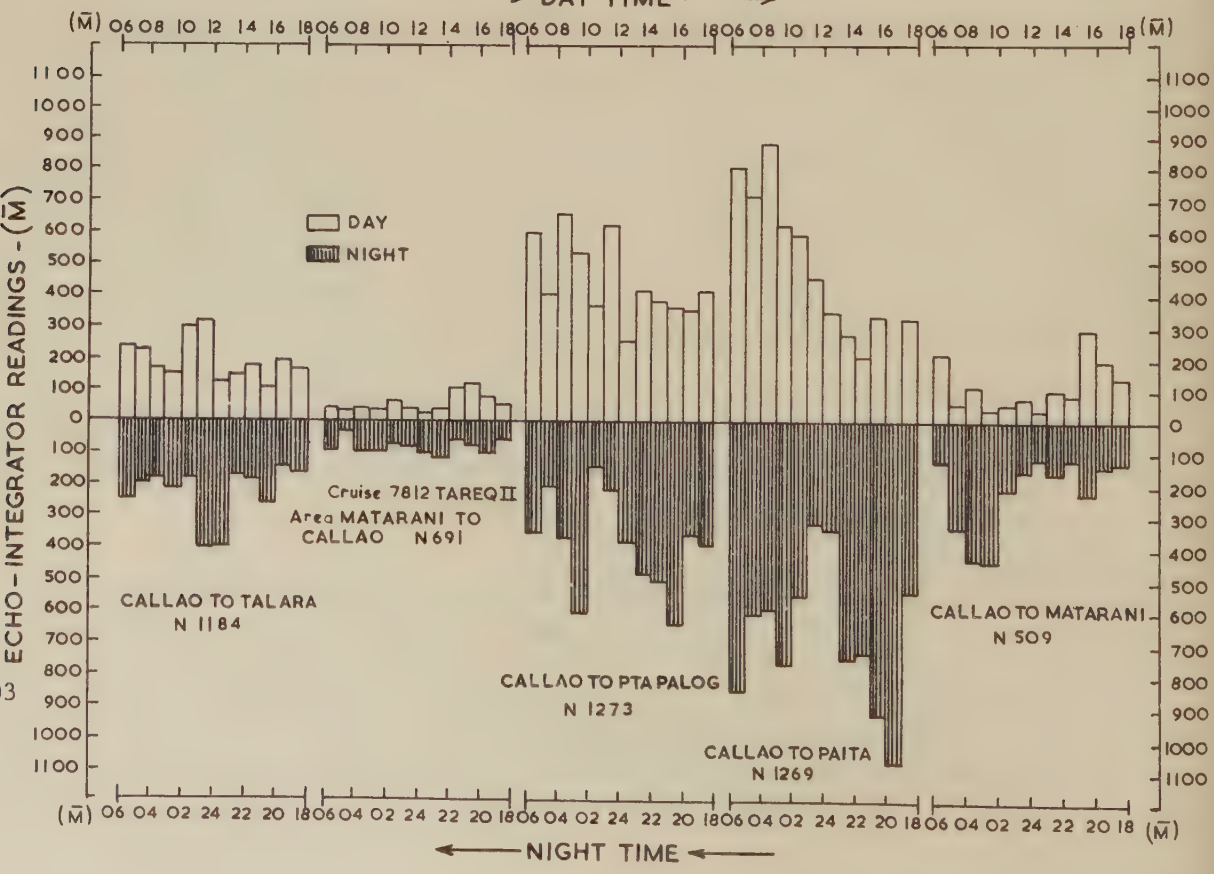


Figure 103

aid the process. Clearly, numerous types of graph could be constructed in an attempt to elucidate the diurnal variability, but only three such examples are included in this manual. These are shown in Figures 103-4-5 which illustrate the night/day differences by hour, by day/night and by density stratum.

Figure 104

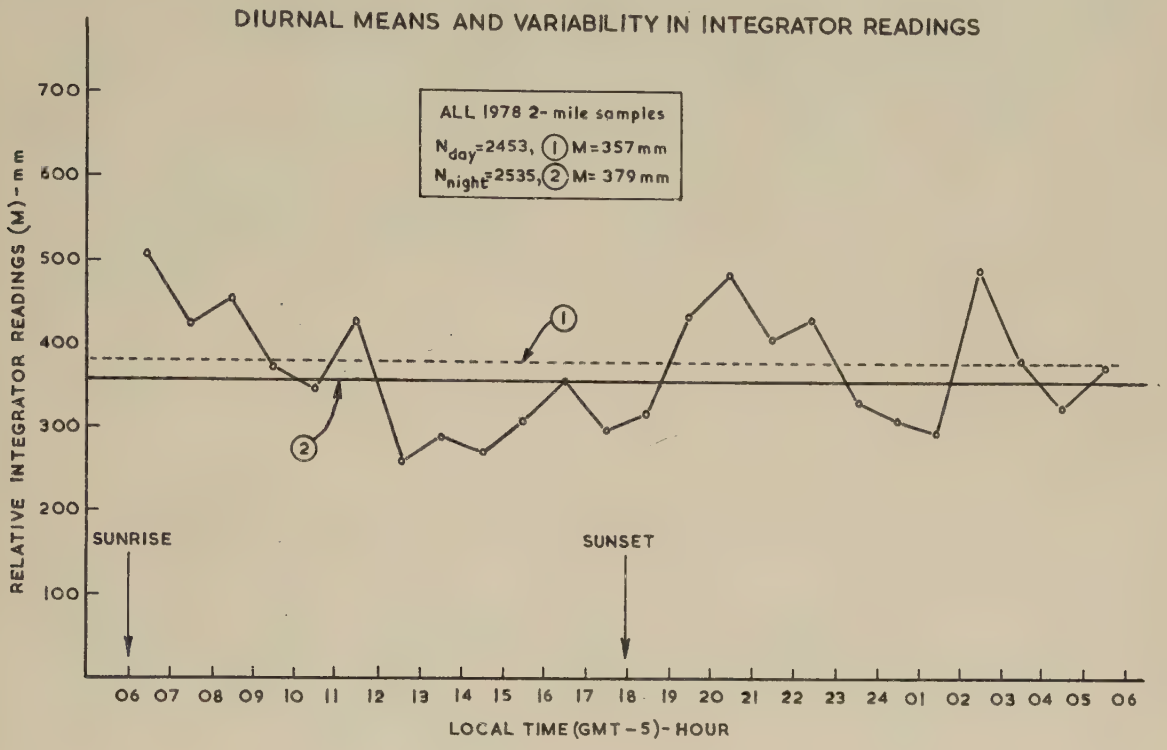
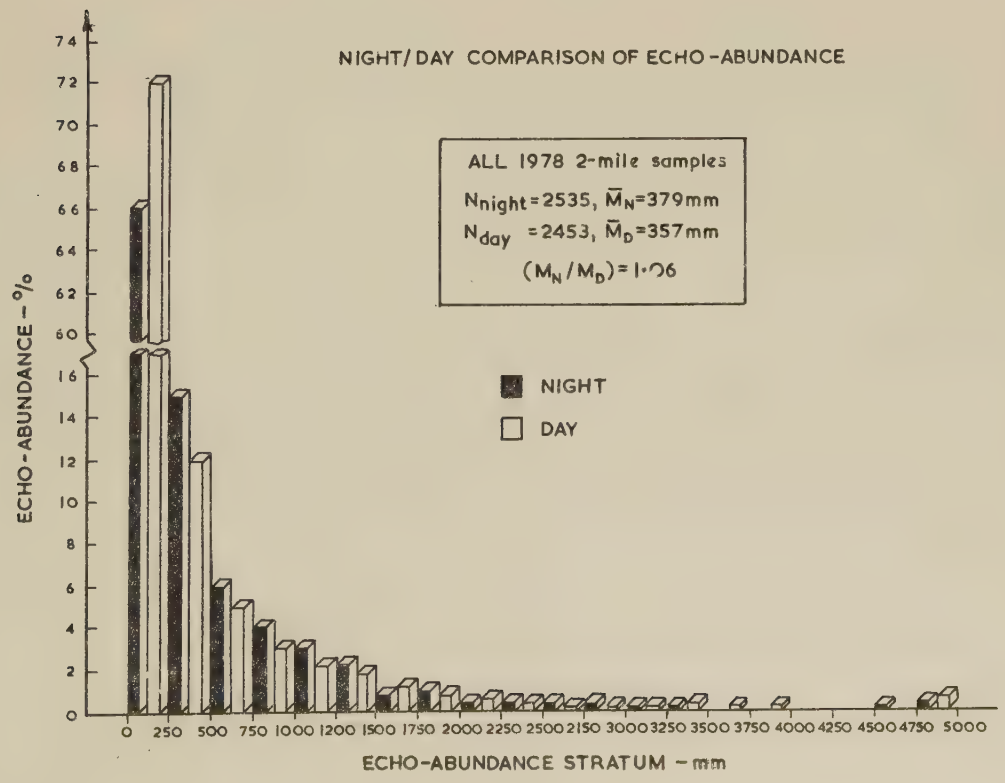


Figure 105



10.2 Derivation of Estimates

The previous section dealt with analytical procedures leading to results in the form of distribution maps and graphs, whereas the present section deals with numerical analyses for the derivation of stock estimates. Referring to Figure 90, this takes us back to the plotted chart of M observations presented in Figure 92. In Chapter 6 of this manual, we saw that the equation for fish biomass (W_B) of a given species within an area A, can be written in a simple form (Midttun and Nakken, 1977)

$$W_B = C \bar{M}_A \int A \; dA \qquad \ldots\ldots\ldots\ldots (88)$$

where C is the integrator scaling factor for the target species and $\bar{M}_A$ is the mean integrator value within the planimetrically integrated area A. The alternative way for numerical derivation of biomass estimate from a data base as plotted in Figure 92, is to employ the relationship

$$W_B = \bar{\rho} \int A \; dA$$

$$= 10^{0.1 (10 \log \bar{M} - 10 \log G_e - 10 \log C_i - \overline{TS})} \; (\int A \; dA) \qquad \ldots\ldots\ldots (89)$$

The first factor in the above product represents a rewriting of equation 59 from 6.4. This form for the estimation of biomass relies on a step-by-step calibration of the integrator system together with a knowledge of mean target strength for the relevant fish species. In the following, only equation 88 and its implications will be discussed.

10.2.1 Scaling Factor 'C'

The different methods for establishing the scaling factor C were detailed in Chapter 6 and the implications of the associated errors specifically treated in 9.4 of this manual. It is also important to be aware of biological processes that can play a significant role in the accuracy and the range of application of a given C value. To examine the problem more closely it is convenient to distinguish between four cases as follows:

a. C obtained from a technically successful live fish calibration experiment on a representative sample in terms of species and size distribution.

b. C established for one particular species but applied to another species of similar size distribution (caution is needed).

c. C established for one narrow size-class, say, 19-20 cm but applied for the entire target stock with size distribution from 6-20 cm.

d. C obtained for one particular species of small size but also used for several larger species in the same survey area.

An evaluation of the above cases would first conclude that case (a) can be considered free of direct biological implications. As for (b), since the species are

of similar size, a bias in C could arise as a result of differences in morphology particularly in relation to the swimbladder. Consequently, such differences should be investigated to assess the accuracy of using C for the second species.

In regard to (c) and (d) the broad application of C can be significantly influenced by length-dependent biases so that some correction will be required. Also, in case (d) morphological factors may introduce further bias if these are not taken into account.

The length-dependence of the scaling factor C is of great importance in acoustic stock assessment work and a better understanding of this relationship is necessary for control and correction of potential errors. A review of the theory, followed by a case study based on data from the Icelandic capelin research, illustrates the principles involved. First, we recall equation 56

$$\rho_v \Delta R = M/G_e C_i (\sigma/4\pi)$$

which, for the present purposes, we can write in the form

$$\rho_v = K (M/\sigma)$$

where K represents a lumped constant. We are interested in the cross section per unit weight, i.e. $(\sigma/4\pi)/W$ where W is the weight of the fish. The weight/length and the cross-section/length relationship can be expressed as follows:

$$\sigma = a_1 \ell^{P_1} \quad \text{and} \quad W = a_2 \ell^{P_2}$$

where ℓ is the length of the fish species.

Subscituting in the above equation gives:

$$\rho_v = K M (a_2/a_1) \ell^{(P_2 - P_1)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (90)$$

Cross-section per unit weight can be misleading because $P_1 \approx 2.5$ and $P_2 \approx 3$. If $\ell^{P_2-P_1} = 1$, ρ_v is exclusively a function of M but usually $(P_2-P_1) \neq 0$ so the density estimator becomes length dependent. Clearly this can be corrected if the functional relationship between ℓ and the two variables (σ,W) is known. For the weight this is usually the case, while for the scattering cross-section (σ) this may require a special investigation. It is better though to use TS per fish where the fish length is in cm, then

$$TS = m \log \ell + b$$

where $m \approx 20$ and b is a constant related to species and acoustic frequency. However,

with increasing knowledge of the TS/length relationship in the form of published data, it is generally feasible to adjust the scaling factor C for variations in fish length. One approach, which has found application in investigations of the Barents Sea capelin stock (Nakken and Dommasnes, 1975) is to operate with a collective constant C' which mathematically is expressed as a function of individual scaling factors C_1, C_2, C_3 ..... C_n and the proportional length groups (year-classes) obtained from catch samples. To explain the principle involved in detail, let the individual densities of several year-classes be denoted by:

ρ_{A_1}, ρ_{A_2}, ρ_{A_3}, ... ρ_{A_n} when measured along a vessel's survey track, or in a given survey area. We define the integrator reading M' as the value produced collectively by the n year classes and the proportion of each class: K_1, K_2, K_3 ..... K_n so that their total sum equals one, i.e. $(K_1 + K_2 + ... K_n) = 1$. Given the above definitions, it can be shown by simple algebra that

$$\rho_{A_1} = K_1 C' M' \qquad \text{..... (91)}$$

$$\rho_{A_2} = K_2 C' M'$$

$$\rho_{A_n} = K_n C' M'$$

where the constant C' is given by the expression

$$C' = (K_1/C_1 + K_2/C_2 + K_3/C_3 ..... K_n/C_n)^{-1} \qquad \text{..... (92)}$$

An example of the practical application of this method is given below using data from joint Icelandic/Norwegian surveys of the Icelandic stock of capelin (Vilhjalmsson et al. 1982). From these data:

$$\bar{W} = a_2 \ell^{P_2} = 0.00178 \times 10^{-6} \times \ell^{3.4} \text{ (tonnes)}$$

as illustrated graphically in Figure 106.

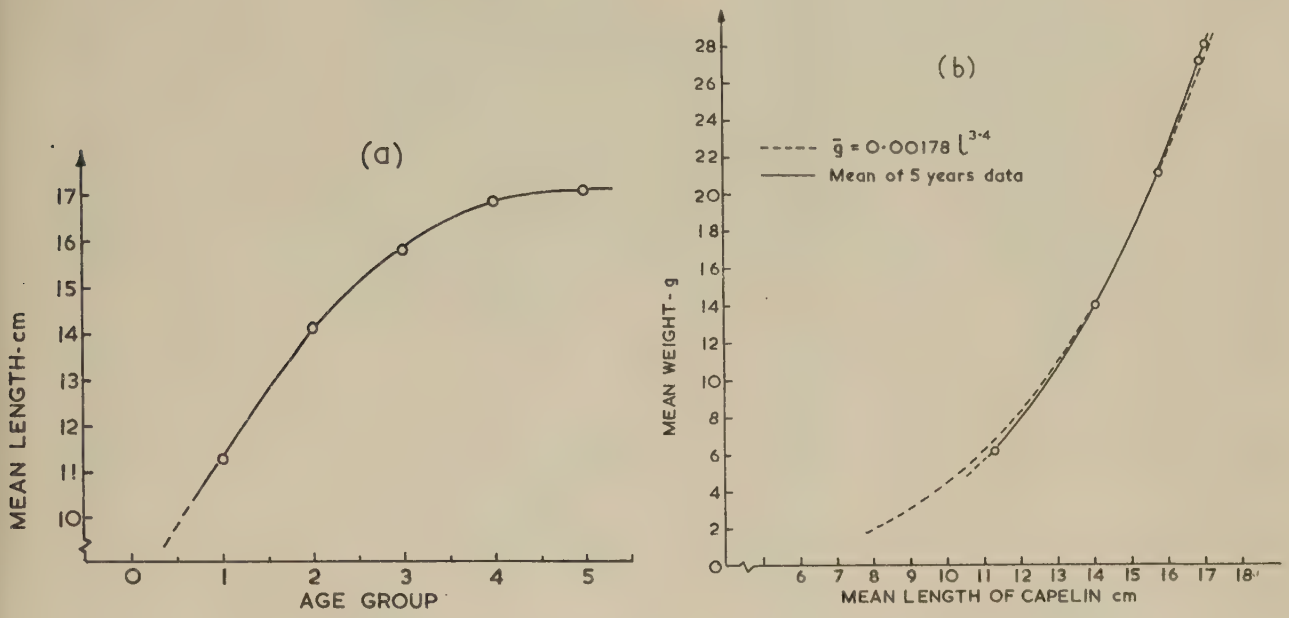
Secondly, the scaling factor C_f expressed in terms of numbers of fish per square-nautical mile referred to 1 mm integrator deflection is related to fish length as follows:

$$C_f = 8.1 \times 10^6 \times \ell^{-1.91} \text{ (fish/mile}^2\text{/mm)}$$

Hence, the scaling factor C_f expressed in terms of biomass is readily calculated from

$$C = C_f \times \bar{W} = 0.0144 \times \ell^{1.49} \text{ (tonnes/mile}^2 \text{ per mm)}$$

Figure 106

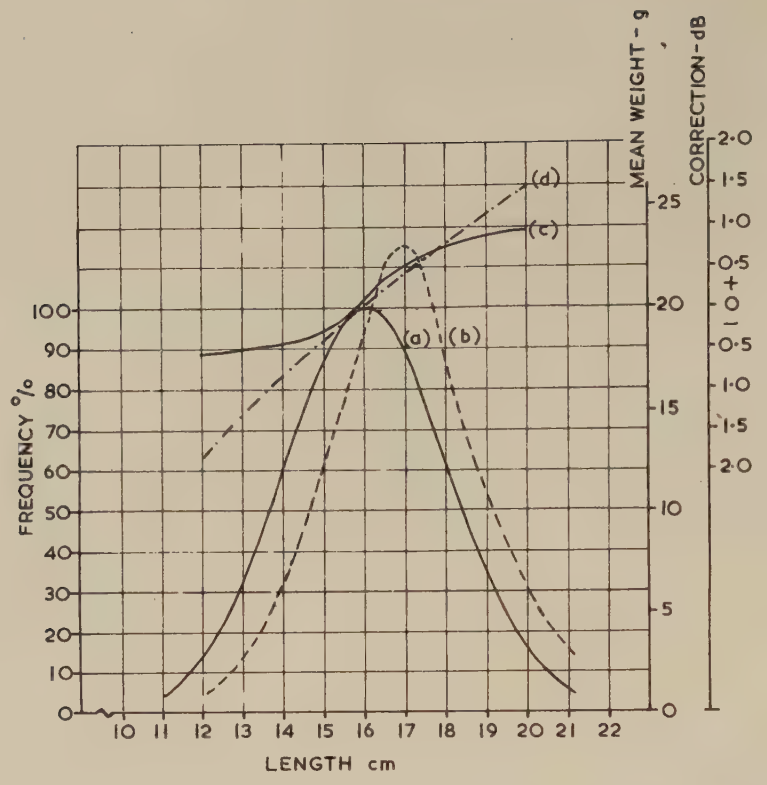


Using this expression and the graphic data in Figure 106a we can calculate the scaling factor C for the mean length of each year-class as follows:

age-group	mean length (cm)	scaling factor
1	11.3	$C_1 = 0.534$
2	14.1	$C_2 = 0.743$
3	15.8	$C_3 = 0.880$
4	16.9	$C_4 = 0.973$
5	17.1	$C_5 = 0.990$

The theoretical variations in C with length is further illustrated by a self-explanatory set of graphs presented in Figure 107. Given that our main interest is to examine the overall theoretical variability in the collective constant C' (equation 92) we can adopt four hypothetical catch samples with distinct age-group compositions as shown in Figure 108. A set of K_1, K_2, K_3 and K_4 values is readily deduced for each of the four samples. Using the corresponding values of C_1, C_2, etc., and equation 92, the resulting values of C' can be calculated.

Figure 107



(a) Theoretical normal curve for length distribution of capelin;
(b) corresponding weight distribution using data from previous figure
(c) corresponding length correction of calibration constant in dB
(d) theoretical correction in dB, assuming equal weight ratio of all year-classes.

(a) Theoretical normal curve for length distribution of capelin
(b) corresponding weight distribution using data from previous figure
(c) corresponding length correction of calibration constant in dB
(d) theoretical correction in dB, assuming equal weight ratio of all year-classes

$$C_1' = \left[(0.1/0.534) + (0.3/0.743) + (0.4/0.88) + (0.2/0.973)\right]^{-1} = (1.2517)^{-1}$$

$$C_1' = 0.799$$

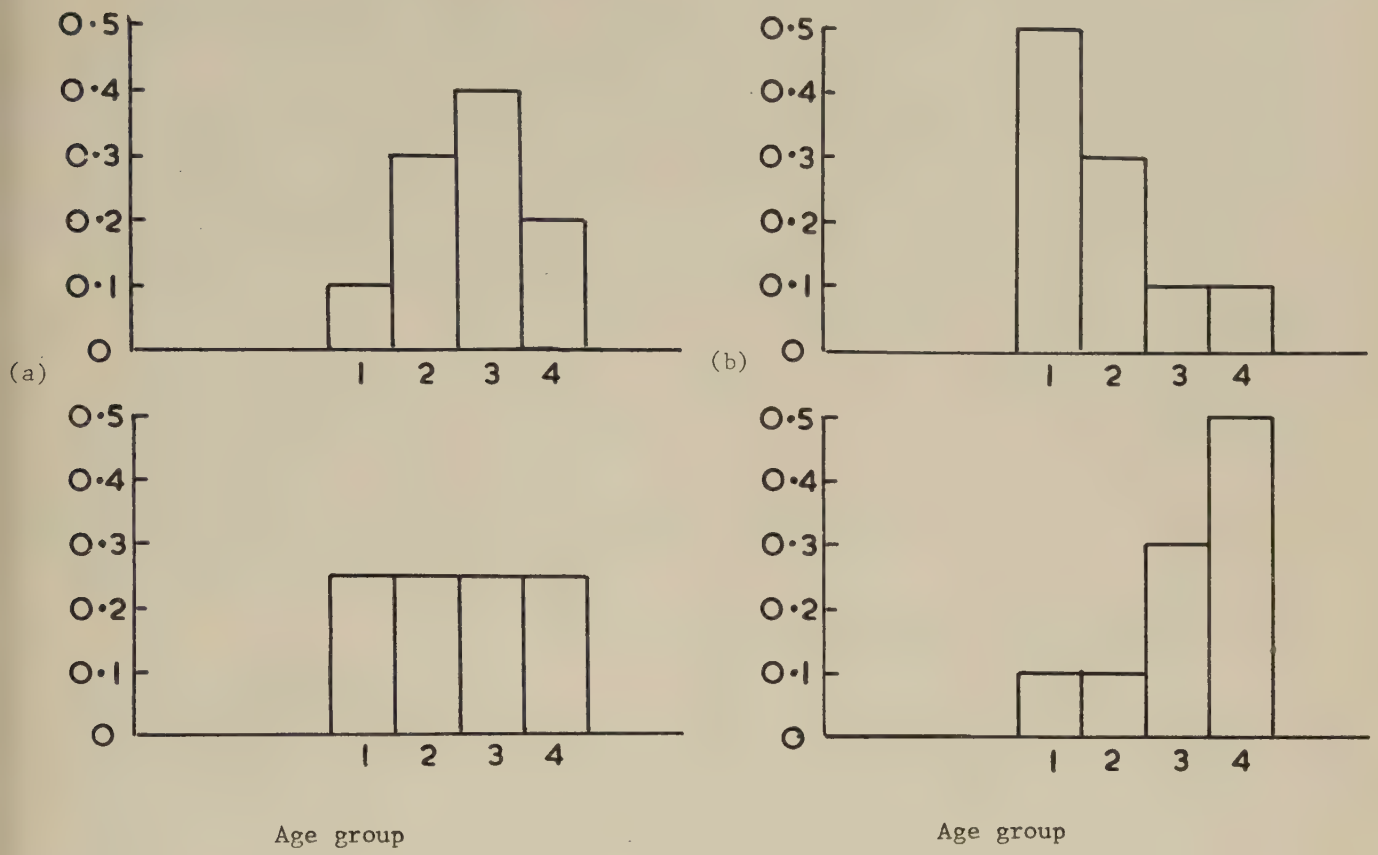
Repeating for the three remaining samples we get

$$C_{II}' = 0.744$$
$$C_{III}' = 0.643$$
$$C_{IV}' = 0.851$$

The relatively modest level of variability in the above test values (C.V. = 11.7% about a mean of 0.759) suggests that, unless there are major changes in length frequencies from one sample to the other, the numerical value of C' remains relatively constant. But it also becomes evident that if the population being surveyed has for example a bimodal size distribution, appropriate corrections of C' would become essential.

The successful application of a length dependent scaling factor C' as defined above requires that (a) frequent catch samples be taken during a survey, (b) the samples be

Figure 108 Proportional weight ratio of year classes of capelin



representative and thus free of bias due to gear selectivity. With these criteria fulfilled, the variations in C' (with species, length-group and their proportional weighting factors) can be calculated on the basis of equation 92.

10.2.2 Simple Random Sample

We recall that the estimator for biomass (W_B) in a given area (A) is commonly expressed in the form

$$W_B = \bar{M}\, C\, A$$

This expression implies that if the scaling factor C, and the area A, can be accurately determined, and also a representative mean value ($\bar{M}$) can be derived, then an unbiased estimate of W_B will result. Referring to Figure 92 the problem is to estimate the parameter $\bar{M}$ from the plotted set of data M_1, M_2, M_3 ....M_n, where each sample value is considered a statistically independent estimate of the relative biomass. If these samples represent a truly random and representative selection from the target population, an unbiased estimate of the population mean would be given simply by

$$\bar{M} = \sum_{i=1}^{n} M_i/n$$

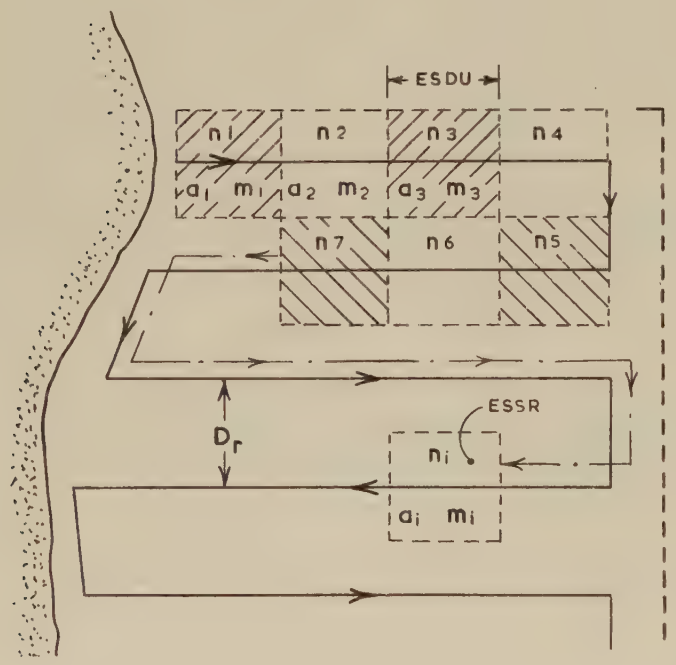
i.e., the random sample mean. However, this is rarely so with acoustic survey data due to the systematic nature of the sampling. Biological situations contain contagious

distributions which are random, the fish are randomly distributed within groups and the groups are randomly distributed.

The set of data shown in Figure 92 demonstrates the possible level of bias involved by first treating the observations (M_i) as a simple random sample and then in 10.2.3 to re-calculate the estimated magnitudes on the basis of a stratified random sample for comparison. Two approaches can be adopted for the simple-random-sample estimate, often referred to as the geometric versus the algebraic method, depending on the way in which the population distribution area is determined. The two methods can be described as follows:

i) Algebraic Method

Figure 109



The basic principle is schematically illustrated in Figure 109. Each sample observation (M_i) is assigned to a corresponding rectangular area, here called "elementary statistical sampling rectangle" (ESSR).

For a parallel survey grid with equidistant inter-transect spacing (D_T) all ESSR's will have equal area sizes given by

$$\text{ESSR} = D_T \times (\text{ESDU}) \quad \text{mile}^2$$

where ESDU is the selected "elementary sampling distance unit" as described earlier. When the inter-transect spacing equals one ESDU, it follows that the ESSR becomes a square of size $(\text{ESDU})^2$. Given that zero observations ($M_i = 0$) are also counted then the total area A, is calculated as: $A = a_1 + a_2 + a_3 + \ldots\ldots\ldots a_N$, or

$$A = \sum_{i=1}^{N} a_i$$

where N is the total number of ESSR's. Likewise, the mean of all observations is given by

$$\bar{M} = \frac{1}{N} \sum_{i=1}^{N} M_i$$

and the total biomass

$$W_B = \bar{M}\ C\ A = \bar{M}\ C\ N\ (ESSR)$$

It should be noted that the area is determined as the algebraic sum of all ESSR's and hence the algebraic method.

ii) Geometric Method

The calculation of the mean is done in the same way except that only values of $M_i \neq 0$ are counted, hence

$$\bar{M} = \frac{1}{N} \sum_{i=1}^{N} M_i$$

where N is now the total number of actual biomass observations.

The total biomass is then given by

$$W_B = \bar{M}\ C \int_A dA = \bar{M}\ C\ A$$

where the total area of distribution, A, is determined through geographic integration, e.g. by using a planimeter.

Applying the latter method to the plotted survey data of Figure 92 we obtain

Sample mean: $\bar{M} = 228.2$

Standard deviation: $S_{\bar{M}} = \left(\sum_{i=1}^{N} (M_i - \bar{M})^2/(N - 1) \right)^{\frac{1}{2}} = 469.4$

variance: $V(\bar{M}) = \frac{S^2_{\bar{M}}}{N} = \frac{(469.4)^2}{364} = 605.3$

95% confidence interval: $C.I. = \bar{M} \pm 1.96 \times (V\ \bar{M})^{\frac{1}{2}}$

$= 228.2 \pm 48.2$ mm or C.I. = (180.0 - 276.4) mm

Hence, the percentage bounds are ± 21.1% of the mean which can be compared with the stratified estimation procedure discussed in section 10.2.3.

The corresponding area size and scaling factor was

C = 0.78 tonnes/nautical mile^2 per mm

A = 16,500 nautical mile^2

So, in terms of biomass (W_B)

$$C.I. = \bar{M}\, C\, A \pm 1.96\, C\, A \sqrt{(V\, \bar{M})}$$
$$= 2{,}936{,}934 \pm 620{,}334$$

Thus, giving lower and upper limits:

C.I. = (2,316,600 - 3,557,268) tonnes

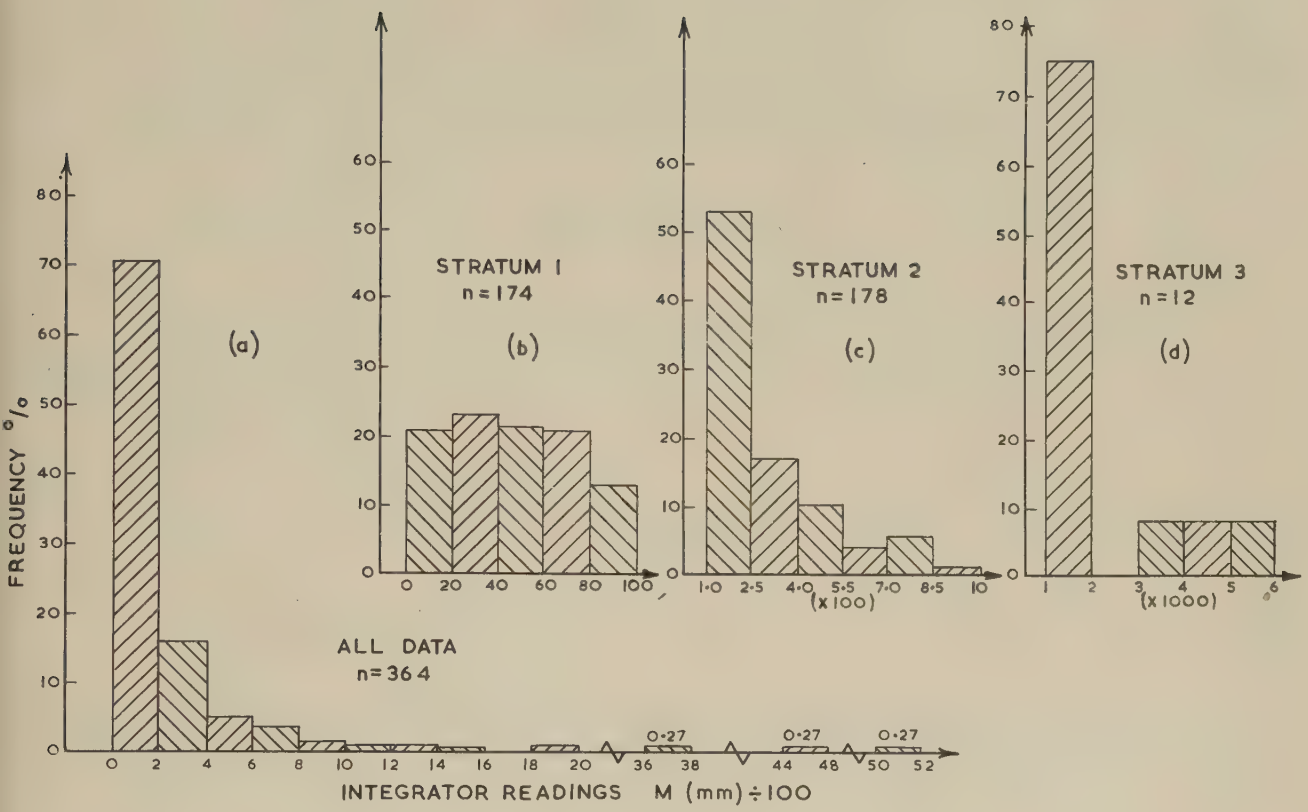
10.2.3 Post-Sampling Stratification

An a priori stratification of sampling effort is difficult to achieve, (section 8.2 on the "Planning and Design of Surveys"). Consequently, a post-sampling stratification is commonly applied with the aim of increasing the precision of acoustic biomass estimates. Such a procedure is particularly expedient for survey data exhibiting heterogeneous distribution in terms of mean density and variance. Provided it is possible to divide the survey observations (and hence the surveyed fish population) into strata of greater homogeneity, the level of precision for interstratum estimates will be enhanced. Estimates of total biomass, with improved precision, are then obtained by combining estimates for all strata.

An attempt to post-stratify sample observations should begin with a study of their frequency distribution. Figure 110 shows a graphic illustration of the frequency characteristics of data used for calculation of the random sample mean in the previous chapter. Intuitively, the extreme positive skewness of the frequency distribution makes it unrealistic to adopt an arithmetic mean as a representative parameter. Also, a visual evaluation of the histogram does not suggest any natural division of these data. When this is the case and observations are wide ranging, it is customary to establish strata on the basis of logarithmic divisions as shown in the example below:

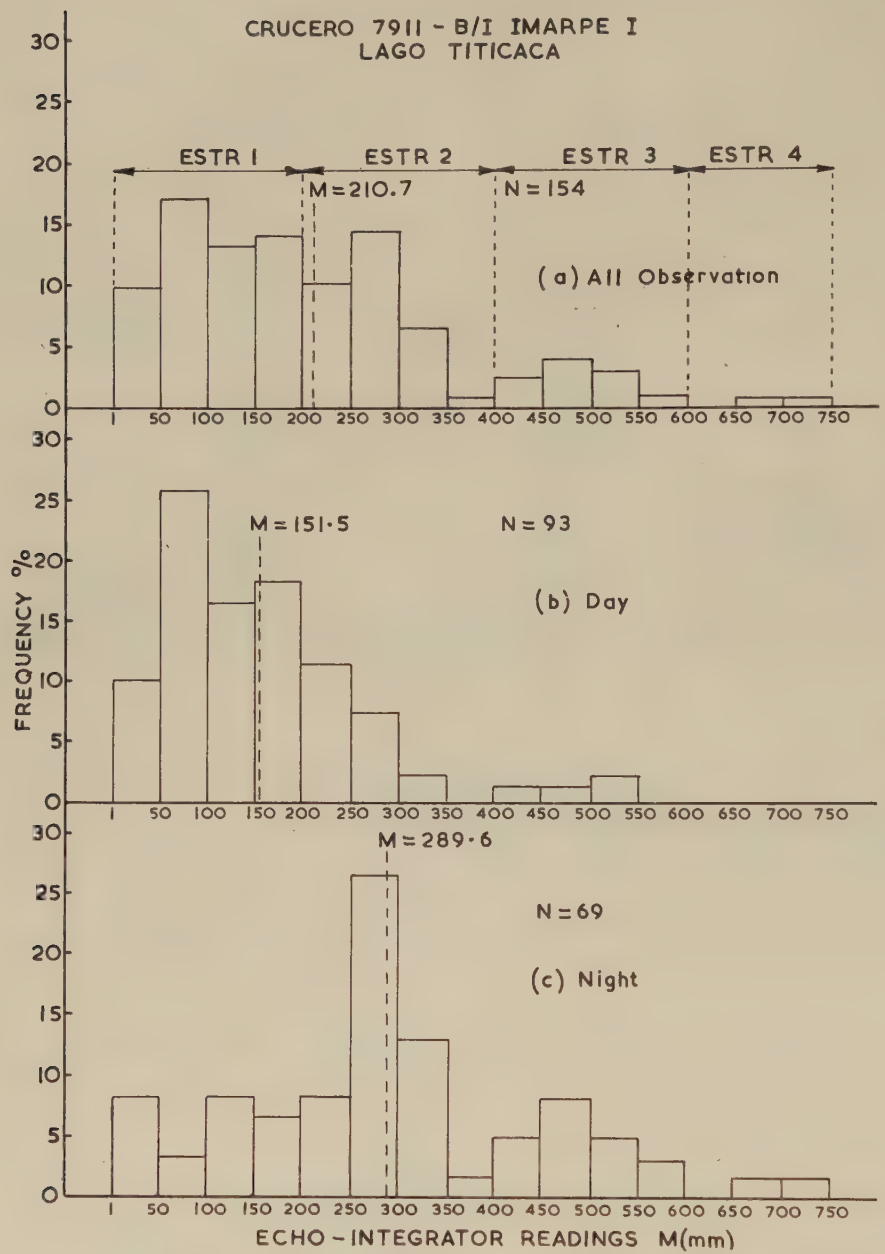
Stratum (h)	M-values (mm)	Abundance description
1	1-10	very scattered
2	11-100	scattered
3	101-1000	dense
4	1001-10000	very dense

Figure 110



In other types of surveys, the frequency plots can give direct guidance to the selection of strata size and numbers as in Figure 111; the frequency distribution of data obtained during a survey of Lake Titicaca, Peru, (Johannesson, 1981). Figure (a) shows a set of four strata established on the basis of visual evaluation of the overall data histogram. The estimate resulting from these data demonstrated a relatively high level of precision (C.I. ± 4.5%, p = 0.95). Once the strata have been formed, the estimation procedure is as follows: First define the echo abundance (E) in the area, i.e. $E = \bar{M} A$, where A is defined by the density isolines. Because we are post-stratifying the M-observations for analytical purposes, it often happens that a given stratum, by our definition will result in more than one separate geographic area when the corresponding M isolines are constructed. For example in Figure 94 where the 3rd stratum (401-600 mm) has turned into six separate areas which we call sub-areas. Hence, the 3rd stratum comprises six sub-areas and the size of the stratum area is the sum of these. In practice, the area sizes are calculated by way of planimetric integration.

Figure 111. Frequency distribution of integrated echo intensities



(a) all observations
(b) day integrator readings
(c) night readings

The echo abundance (E_{h_j}) within the j^{th} sub-area, in the h^{th} stratum is

$$E_{h_j} = A_j \sum_{i=1}^{i} (M_{j_i}/n) \qquad \text{..... (93)}$$

where:

j = index for sub-area
n = number of M values within the j^{th} sub-area
A_j = area size of the j^{th} sub-area (mile^2)
M_{j_i} = i^{th} sample of M within the j^{th} sub-area

The total echo abundance within stratum is found by summation

$$E_h = \sum_{j=1}^{j=m} E_{h_j} \qquad \ldots\ldots\ldots\ldots\ldots (94)$$

where m = number of sub-areas within stratum. Further, the total echo abundance in the area surveyed (E_t) is found by the summation

$$E_t = \sum_{h=1}^{L} E_h \qquad \ldots\ldots\ldots\ldots\ldots (95)$$

where L is the total number of strata. Finally, the conversion into total biomass (W_{B_t}) is obtained from the product

$$W_{B_t} = C\, E_t$$

where C is the scaling factor as before.

Using the above method with data presented in Figure 110(a) we select the following strata:

Stratum 1 : 11-100 mm
Stratum 2 : 101-1000 mm
Stratum 3 : 1001-10000 mm

Frequency histograms representing the individual strata are shown in Figure 110b,c,d and all 364 M-observations are tabulated, by stratum, in Table 10. A summary of the results of the relevant calculation is given as

Table 9

Stratum (No.)	No. of Samples (n_h)	Area mile^2 (A_h)	Mean int. value $\bar{M}_h$	Variance $V(\bar{M}_h) = S^2_{\bar{M}}/n_h$
1	174	9,200	47.5	3.7
2	178	7,000	274.8	195.0
3	12	300	2,157.1	174,315.0
Total:	364	16,500		

Total echo abundance $E_t = E_{h_1} + E_{h_2} + E_{h_3}$ = 9,200 x 47.5 + 7,000 x 274.8 + 300 x 2,157.1 = 3,007,638

Total biomass estimate $\bar{W} = C\, E_t$ = 0.78 x 3,007,638 = 2,345,957 (tonnes)

Table 10
Acoustic data corresponding to frequency histograms in Figure 110(b, c and d), used for calculation of stratified estimates

Stratum I						n = 174			
Obs (No)	M (mm)	Obs (No)	M (mm)	Obs (No)	M (mm)	Obs (No)	M (mm)	Obs (No)	M (mm)
1	26	37	48	73	64	109	54	145	62
2	34	38	48	74	27	110	80	146	41
3	18	39	10	75	19	111	54	147	19
4	19	40	11	76	27	112	89	148	24
5	55	41	12	77	21	113	70	149	51
6	56	42	65	78	11	114	71	150	55
7	18	43	60	79	24	115	54	151	13
8	10	44	18	80	82	116	66	152	66
9	50	45	35	81	96	117	70	153	22
10	75	46	19	82	85	118	82	154	13
11	70	47	41	83	60	119	75	155	80
12	93	48	37	84	41	120	28	156	51
13	45	49	83	85	49	121	86	157	12
14	25	50	90	86	11	122	20	158	80
15	63	51	91	87	24	123	27	159	82
16	41	52	69	88	16	124	55	160	50
17	19	53	61	89	87	125	42	161	68
18	38	54	82	90	72	126	59	162	34
19	84	55	40	91	59	127	10	163	40
20	52	56	24	92	25	128	30	164	13
21	55	57	64	93	23	129	13	165	17
22	17	58	90	94	30	130	71	166	20
23	83	59	15	95	35	131	21	167	10
24	67	60	47	96	54	132	93	168	20
25	70	61	29	97	30	133	57	169	12
26	24	62	52	98	21	134	87	170	27
27	75	63	54	99	88	135	45	171	19
28	21	64	42	100	59	136	64	172	19
29	12	65	44	101	28	137	40	173	38
30	30	66	27	102	75	138	37	174	74
31	16	67	62	103	76	139	24		
32	54	68	68	104	28	140	16		
33	82	69	75	105	34	141	87		
34	69	70	91	106	77	142	77		
35	83	71	75	107	35	143	17		
36	79	72	83	108	56	144	31		

Table 10 (contd)

Stratum II									n = 178
Obs (No)	M (mm)	Obs (No)	M (mm)	Obs (No)	M (mm)	Obs (No)	M (mm)	Obs (No)	M (mm)
1	131	37	186	73	173	109	492	145	142
2	128	38	188	74	196	110	410	146	191
3	260	39	702	75	118	111	241	147	154
4	408	40	154	76	150	112	285	148	216
5	123	41	679	77	345	113	525	149	165
6	250	42	805	78	345	114	288	150	121
7	380	43	169	79	418	115	279	151	205
8	123	44	126	80	504	116	184	152	114
9	250	45	225	81	220	117	135	153	138
10	209	46	119	82	205	118	298	154	385
11	205	47	242	83	171	119	530	155	780
12	315	48	102	84	121	120	208	156	935
13	146	49	197	85	319	121	101	157	675
14	213	50	640	86	150	122	112	158	102
15	211	51	128	87	130	123	119	159	128
16	250	52	760	88	500	124	103	160	578
17	163	53	180	89	270	125	264	161	187
18	535	54	245	90	101	126	321	162	254
19	490	55	245	91	725	127	464	163	270
20	735	56	338	92	110	128	101	164	189
21	728	57	455	93	180	129	143	165	272
22	276	58	148	94	175	130	230	166	222
23	155	59	250	95	167	131	282	167	372
24	128	60	101	96	146	132	810	168	714
25	115	61	175	97	157	133	550	169	376
26	116	62	209	98	237	134	147	170	131
27	140	63	619	99	185	135	150	171	111
28	205	64	180	100	248	136	450	172	495
29	254	65	120	101	174	137	270	173	504
30	112	66	196	102	238	138	110	174	145
31	306	67	186	103	117	139	123	175	324
32	640	68	168	104	110	140	618	176	250
33	181	69	310	105	229	141	188	177	285
34	115	70	115	106	826	142	129	178	216
35	294	71	149	107	418	143	105		
36	209	72	419	108	101	144	106		
Stratum III									n = 12
1	1040								
2	1375								
3	1435								
4	4655								
5	1070								
6	1150								
7	1845								
8	1920								
9	3725								
10	1340								
11	1310								
12	5020								

Stratified variance estimate:

$$V(\bar{M}_{st}) = \sum_{h=1}^{L} V(\bar{M}_h)(A_h)^2$$

$$= 3.7 \times 9{,}200^2 + 195 \times 7000^2 + 174{,}315 \times 300^2$$

$$= 2.5557 \times 10^{10}$$

Confidence interval of the stratified estimate:

$$C.I. = \bar{W}_{B_t} \pm t_{.95} \times C \times (V\ \bar{M}_{st})^{\frac{1}{2}}$$

$$= \bar{W}_{B_t} \pm 1.96 \times 0.78\ (2.557 \times 10^{10})^{\frac{1}{2}}$$

= 2,345,957 and 244,455 tonnes

Thus, giving lower and upper limits:

C.I. = (2,101,502 - 2,590,412) tonnes

Hence, the percentage bounds are now reduced to ± 10.4%

Comparison of the results from the two different methods of analysis brings out two important factors,

(1) the stratification has produced a 10.7% gain in precision

(2) the estimate of total stratified biomass is about 20% lower than the non-stratified result. This decrease in the point estimate attests to the fact that stratification also increases the accuracy of population estimates and ensures that subdivisions (strata) of the population are adequately represented.

It is instructive to compare the stratum graphs (Figure 110-b,c,d) with the individual stratum variances as tabulated above. From the histogram for stratum 1, one would expect a low variance whilst for the heterogeneous character of the frequency distribution in stratum 3, one would expect a high level of variance which is confirmed by the coefficient of variance (C.V. = $(S_{\bar{M}}/n) \times 100$) for the individual strata calculated as follows:

Stratum 1 : C.V. = 14.6%

Stratum 2 : C.V. = 104.7%

Stratum 3 : C.V. = 12,050.0%

These comparisons elucidate the importance of the formation of homogeneous strata for achieving satisfactory numerical biomass (population) estimates.

10.3 Statistical Implications and Limitations

In 10.2 we applied two different approaches (stratified and non-stratified) to derive point estimates for total biomass and then calculated the associated statistical variance and confidence limits. Formulae from standard statistical text-books, were used without qualification of their suitability for specific methods of sampling and estimation. For example, it was assumed that the 'M' as a variable would follow a normal

distribution and hence symmetrical confidence intervals about the estimated mean ($\bar{M}$) would exist. Likewise statistical independence of the samples was assumed, thus the effects of possible auto-correlation between the successive samples were ignored. These and other factors of a statistical nature may significantly influence the precision and accuracy of fish biomass estimates and, in particular, lead to unreliable interval estimates (C.I.) if the methods of analysis are inefficient.

10.3.1 Transformation of Sample Observations

Much of the useful theory of sampling turns around the Normal Law, i.e. the normal distribution of Gaussian distribution defined by the equation

$$y = \left[\sigma(2\pi)^{\frac{1}{2}}\right]^{-1} e^{-0.5\,(x-\mu)^2\,(\sigma^2)^{-1}}$$

where μ = mean and σ = standard deviation.

Thus, for a valid statistical analysis of variance about an estimated mean ($\bar{M}$, point estimate), the distributions must be of such character as to have means independent of the variance, i.e. to exhibit an approximately normal distribution. Distributions which depart seriously from the normal type (usually in fisheries acoustics by being excessively skewed in a positive direction), may require the technique of 'transformations' to be used to force the data into a better approximation to normality. Generally, this process can serve either or both of two main purposes to obtain

(a) a variable of increased practical relevance, e.g. for variance analysis

(b) a variable with satisfactory approximation for further mathematical modelling of data, eg. linear regression, or describe distribution patterns.

A full consideration of (a) and (b) require concepts too advanced for this manual so we deal with the first situation (a) with special reference to acoustic data. Only the typical positive skewness in acoustic data and the relevance of using transformations for their approximate normalization has been shown and two questions occur

(1) what is the criterion for transformations

(2) what type of transformation to insert for analytical purposes

It has been shown that regardless of the shape or form of a population distribution, the distributions of both the sum and the mean of random samples approaches that of a normal distribution as the sample size is increased. This statement is based on the important theorem known as the central-limit theorem. There is no absolute criterion as to how large the sample (n) must be for use in the normal approximation for computing the variance and confidence intervals. However, Cochran (1975), gives the following crude rule to determine the minimum sample size for populations exhibiting marked positive skewness

$$n > 25\, G_1^2 \qquad \ldots\ldots\ldots\ldots\ldots (96)$$

where G_1 = Fisher's measure of skewness.

$$G_1 = E\,(X_i - \bar{X})^3/\sigma^3 = (1/N\sigma^3)\left(\sum_{i=1}^{N}\{\bar{X}_i - \bar{X}\}\right)^3 \qquad \ldots\ldots\ldots\ldots\ldots \quad (97)$$

(E = expectation = product of sample probability times sample value).

This rule is designed so that a 95% confidence probability statement will be wrong for 6% or less of the time.

Type of transformation

When the sample is too small for the assumption of normality, a transformation is required. The choice of the correct transformation depends upon the original frequency distribution of the data, which is closely related to the spatial distribution of the fish stock from which data are collected. The spatial distribution pattern of fish concentrations are often characterised by their patchiness, or varying combinations of fish aggregations (clumpings) and layers of different densities. This is especially typical for larger pelagic fish stocks. Statistically, such distributions fall in the category of contagious distributions which can be expressed by several mathematical models, eg negative binomial, Polya-Aeppli, Neyman Type and Poisson distribution, as listed in order of decreased positive skewness (Elliott, 1971). Of these, the negative binomial distribution (with its two parameters μ and the exponent k, and having variance greater than mean, $(\sigma^2 > \mu)$ has potential for use with acoustic data, since it can be derived from several mathematical and biological models and thus applied to a wide diversity of contagious distributions. The negative binomial distribution is probably the most suitable model for describing spatial distribution of fish stocks based on acoustic data because these data have a tendency to form a frequency distribution with extreme positive skewness. This, coupled with the fact that the logarithmic series is one of the most skewed of the negative binomial distributions (Elliott, 1971), often suggest a log-normal distribution. Consequently, the appropriate transformation is to form a new variate $M_i = \log x_i$, or $M_i = \log (x_i + 1)$ in case the original variable M_i contains zero values.

More generally the appropriate transformations can be obtained from different distributions, eg Poisson, or the negative binomial distribution as shown in Table 11 below.

Table 11. Transformations obtained from the Poisson and the negative binomial distributions (given by Elliott, 1971).

Distribution			
Original distribution	not known	Transformation	Special conditions
Poisson	$S^2 = \bar{x}$	replace x by $\sqrt{x}$	No counts less than 10
Poisson	$S^2 = \bar{x}$	replace x by $\sqrt{x + 0.5}$	Some counts less than 10
Negative binomial		replace x by $\text{Sinh}^{-1}\sqrt{\frac{x + 0.375}{k + 2.(0.375)}}$	k* greater than 5
Negative binomial	$S^2 > \bar{x}$	replace x by $\log (x + k/2)$	No zero counts
	$S^2 > \bar{x}$	replace x by $\log (x + 1)$	Some zero counts

*k = exponent, interpreted as an index of clumping in the population

However, the general suitability is probably best expressed by Taylors Power Law Taylor (1961) which states that the variance σ^2 of a population is proportional to a functional power of the arithmetic mean μ. Thus

$$\sigma^2 = a\mu^b$$

$$\log\sigma^2 = \log a + b \log\mu$$

Here, 'a' depends chiefly upon the size of the sampling units and 'b' is an index of dispersion which varies continuously from 0 for a regular distribution, to infinity for a highly contagious one. Once 'b' is determined, a common transformation can be applied to the original counts. The appropriate transformation is to replace each count by X^p where $p = 1 - b/2$.

For a log normal distribution b = 2 and p = 0 so we should use a log transformation. Thus if $s_i^2 = a\mu^b = \bar{X}^2$, a = 1 and b = 2 p = 1 - b/2 = 0

The advantages of b with respect to k are

i) the power law covers a wider range of distribution than the negative binomial

ii) the transformations derived from b are often easier to apply than those derived from the negative binomial (Elliott, 1971).

In this connection it can be briefly mentioned that if we make a log transformation such as $M_i = \log X_i$, the so-called null hypothesis is

$$H_o = (y_i - \bar{y})/\sigma_y = Z \sim N(0,1)$$

and the appropriate statistical test for the goodness of fit of a transformation is the χ^2 (chi-square) test or alternatively the non-parametric Kolmogorev-Smirnov test. For a

more detailed study of this subject, the interested reader is advised to consult relevant textbooks on statistics, e.g. Elliot, 1971; Kreyszig, 1970 and Massey, 1951. Also, Bazigos (1975) presents a χ^2-test of acoustic survey data on Lake Tanganyika.

A practical understanding of the above comes by applying the log-transformation to data used in previous calculations of biomass and confidence intervals. First determine whether the sample size (n = 364) fulfills the criteria of eqn. 96. For this purpose we can use grouped data with class-intervals corresponding to the histogram shown in Figure 110(a). Hence, we take the mid-point of each class as a representative mean, moreover we let $M_i = X_i$. A summary of the relevant data tabulation is given in Table 12.

Using equation 97, the computations can proceed as follows:

$$\bar{X} = \frac{\sum f_i X_i}{\sum f_i} = 91400/364 = 251.1$$

$$E(X_i^2) = \frac{\sum f_i X_i^2}{\sum f_i} = 102,120,000/364 = 280,549$$

$$E(X_i^3) = \frac{\sum f_i X_i^3}{\sum f_i} = 326,378,000,000/364 = 896,642,857$$

$$\sigma^2 = E(X_i^2) - \bar{X}^2 = 280,549 - 63,252 = 217,297$$

$$E(X_i - \bar{X})^3 = E(X_i^3) - 3E(X_i^2)\bar{X} + 2\bar{X}^3$$

$$= 896,642,857 - 3 \times 280,549 \times 251.5 \times 2 \times 15,907,941$$

$$= 716,784,518$$

Figure 112

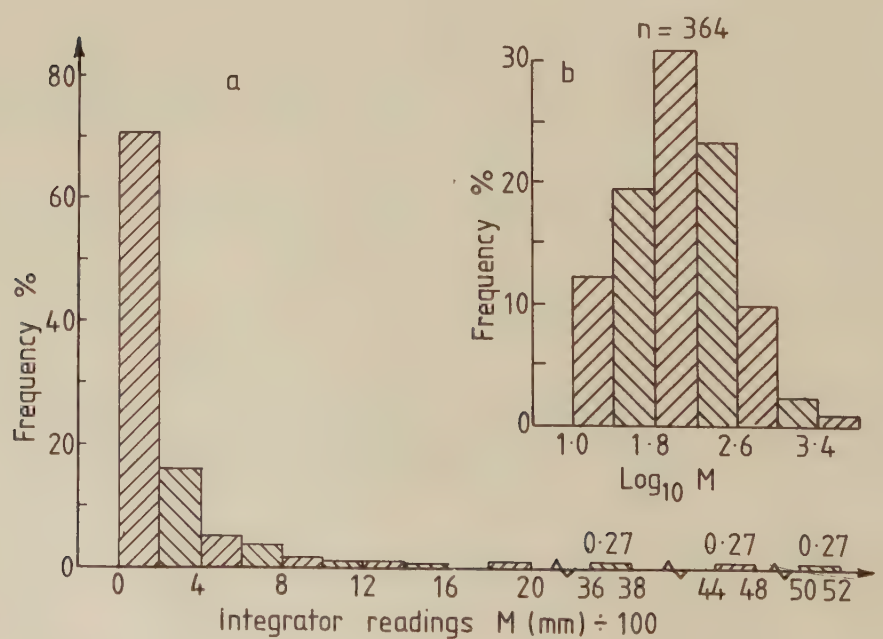


Table 12. Frequency distribution of 'M' using grouped data corresponding to the histogram in Figure 110

Class intervals ΔM	$(M_i = \chi_i)$ χ_i	Freq. f_i	$f_i\chi_i$	$f_i\chi_i^2$	$f_i\chi_i^3$
11- 200	100	258	25,800	2,580,000	258,000,000
201- 400	300	58	17,400	5,220,000	1,566,000,000
401- 600	500	19	9,500	4,750,000	2,375,000,000
601- 800	700	13	9,100	6,370,000	4,459,000,000
801-1000	900	4	3,600	3,240,000	2,916,000,000
1001-1200	1,100	3	3,300	3,630,000	3,993,000,000
1201-1400	1,300	3	3,900	5,070,000	6,591,000,000
1401-1600	1,500	1	1,500	2,250,000	3,375,000,000
1601-1800		0			
1801-2000	1,900	2	3,800	7,220,000	13,718,000,000
		0			
3601-3800	3,700	1	3,700	13,690,000	50,653,000,000
		0			
4601-4800	4,700	1	4,700	22,090,000	103,823,000,000
		0			
5001-5200	5,100	1	5,100	26,010,000	132,651,000,000
Totals:			91,400	102,120,000	326,378,000,000

$$\sigma = \sqrt{\sigma^2} = \sqrt{217,297} = 466.15$$

$$\sigma^3 = (466.15)^3 = 101,292,448$$

$$G_1 = \frac{E(X_i - \bar{X}^3)}{\sigma^3} = 716,784,518/104,292,518 = 7.08$$

Hence, $G_1^2 = (7,08)^2 = 50.13$

So finally

$$n_{min} = 25 \times G_1^2 = 25 \times 50.13 \simeq 1253$$

Considering sample size, we should have obtained at least 1253 observations in order to apply the assumption of normal approximation. An additional factor of interest from this calculation is the standard deviation of the grouped data resulting in a numerical value $\sigma = 466.15$ compared with $S_{\bar{M}} = 469.4$ for the non-grouped data (see section 10.2.2). Some difference must be expected because of slightly changed weighting effects

related to the fact that we have taken the class midpoint as a mean but not the within-class arithmetic mean. Given that our sample of 364 M-values is far too small to justify the assumption of normality, and that the data are highly suggestive of a log-normal distribution, the next step will be to apply the transformation

$$Z_i = \log \dot{X}_i$$

where $\dot{X}_i$ = midpoint value of the classes forming the histogram shown in Figure 112(a). The distribution of the transformed variate and some relevant preliminary calculations are presented in Table 11. Also, a frequency histogram of the new variate (Z_i) is compared with the original data histogram in Figure 112(a-b). The normalizing effect of the transformation is clearly demonstrated by the mode which has moved from the extreme left to the centre of the apparent log-normal distribution. For further analyses we continue as follows:

$$\bar{Z} = \frac{\sum(\log \dot{X}_i)f_i}{n} = \frac{799.1}{364} = 2.20$$

$$S^2_{\bar{z}} = \frac{\sum(Z_i^2 f_i) - \bar{Z} \sum Z_i f_i}{n - 1} = \frac{1796.5 - 2.20 \times 799.1}{364 - 1} = 0.1060$$

$$S_{\bar{z}} = (0.1060) = 0.3256$$

Table 13. Summary of Transformed Data

Interval class $\Delta\chi$	Midpoint class $\dot{X}_i$	freq. f_i	$Z_i = \log \dot{X}_i$	$Z_i f_i$	$Z_i^2 f_i$
11- 200	100	258	2.00	516.00	1032.0
201- 400	300	58	2.48	143.80	356.7
401- 600	500	19	2.70	51.30	138.5
601- 800	700	13	2.85	37.05	105.6
801-1000	900	4	2.95	11.80	34.8
1001-1200	1100	3	3.04	9.12	27.7
1201-1400	1300	3	3.11	9.33	29.0
1401-1600	1500	1	3.18	3.18	10.1
1601-1800	-	0	-		
1801-2000	1900	2	3.28	6.56	21.5
	-	0			
3601-3800	3700	1	3.57	3.57	12.7
	-	0			
4601-4800	4700	1	3.67	3.67	13.2
	-	0			
5001-5200	5100	1	3.71	3.71	13.7
Totals:		364	36.54	799.1	1796.5

After having calculated the mean, variance and the standard deviation of the transformed data, the decoding would seem to involve straightforward antilogarithms giving, for example, a re-transformed mean

$$\bar{X}_g = \text{antilog } \bar{Z} = \text{antilog } 2.20$$

$$= 158.5 \quad \text{geometric mean}$$

However, certain problems arise in transforming back in this way and we can note that the above derived mean (= geometric mean) is about 30% lower than the simple random mean M = 228.2 (see section 10.2.2). Embody (1952) recommends the use of the following formulae

$$10 \log_{10} \bar{X}_A = \bar{Z} + 1.15129 \, S_T^2$$

$$S_A = \bar{X}_A \, (10^{2.302585 \, S_T^2} - 1)^{\frac{1}{2}}$$

where $\bar{Z}$ = the mean of the transformed data

S_T^2 = the variance of the transformed data

$\bar{X}_A$ = the adjusted geometric mean of the retransformed data

S_A = the standard deviation of the retransformed data.

Adopting these we obtain

$$\bar{X}_A = \text{antilog } (\bar{Z} + 1.15129 \, S_T^2$$
$$= \text{antilog } (2.20 + 1.15129 \times 0.1060)$$
$$= \text{antilog } 2.3220$$
$$= 209.9$$

and

$$S_A = \bar{X}_A \, (10^{2.302585 \times 0.1060} - 1)^{\frac{1}{2}}$$

$$= \bar{X}_A \, (10^{0.2441} - 1)^{\frac{1}{2}}$$

$$= 209.9 \times (1.7543 - 1)^{\frac{1}{2}}$$

$$= 209.9 \times 0.8685$$

$$= 182.3$$

The results of applying such statistical corrections to the decoding process can be better evaluated through comparison with the results obtained from the simple-random-sample analyses as shown below:

Parameters / Data Treatment	Est. Mean $\bar{X}$	Est. St. Deviation S	Coeff. Variation C.V.(%)
Simple random sample	228.2	469.4	205.7
Log-normal distribution	209.9	86.3	86.8

One will notice that the re-transformed mean gives a value of $\bar{X}_A = 209.9$, i.e. 8.15% lower than the simple random mean. The second effect of the log-normal data treatment is a significant reduction in variability which in terms of coefficient of variation is now reduced from 205.7% to 86.8%. Given these last figures, the reader will also have noticed that we have already obtained four different estimates of means from the same set of M-data; these are:

(1) Simple random sample mean : $\bar{X}_r = 228.2$

(2) Effective stratified mean : $\bar{X}_{st} = 189.3$

(3) Geometric mean : $\bar{X}_g = 158.5$

(4) Adjusted geometric mean : $\bar{X}_A = 209.9$

These estimates illustrate some of the statistical implications and limitations associated with estimation of representative means (central tendency of the data) from a set of acoustic data points. At the same time the importance of accurate statistical interpretations of the data and their analysis is emphasized.

10.3.2 Confidence Limits for the Estimated Means

In section 8.2.3 it was pointed out that when data from an integrator survey are treated as statistical sample units, each observed integrator reading (X_i) is conceived as an individual sample mean with its own underlying statistics (eg. $\bar{X}_i$), and the entire set of data as a sampling distribution of means. In such a case the sample mean is given by

$$\bar{X}_s = \left(\sum_i^n \bar{X}_i \right)/n$$

where n = number of integrator readings in the sample. The variance is then given by

$$\text{Var}(\bar{X}_s) = s^2/n$$

and the standard error of the means

$$\text{S.E.}(\bar{X}_s) = (s^2/n)^{\frac{1}{2}}$$

where s = standard deviation computed from the familiar formula

$$s = \left(\sum_{i=1}^{n} (X_i - \bar{X})^2\right)/(n-1)$$

The standard error is a parameter of particular interest for the construction of confidence intervals about means since these are in fact expressed in terms of number of standard errors. This can be seen from the general expression for confidence limits, i.e.

$$\text{C.I.} = \bar{X} \pm t_c \, (s^2/(n-1))^{\frac{1}{2}}$$

where the values $\pm t_c$, called critical values or confidence coefficients, depend on the level of confidence (p) desired and the sample size (n). The numerical values for t_c are found in Student's t-distribution (e.g. Pearson & Hartley 1966). Hence we may write

$$\text{C.I.} = \bar{X} \pm t_{p,df} \times \text{(standard error)}$$

where t_c corresponds to the desired probability level (commonly p = 0.95 or 95%) and (n-1) degrees of freedom. For relatively large sample size (n > 30), the coefficient t_c can be replaced by another confidence coefficient z_c, whose numerical values are found directly from the standard normal distribution for a given confidence level; thus for p = 0.95

$$\text{C.I.} = \bar{X} \pm Z_{0.95} \times \text{(standard error)}$$

and for 95% confidence level

$$\text{C.I.} = \bar{X} \pm 1.96 \times \text{(standard error)}.$$

More specifically we lay down our confidence limits as follows:

$$\text{Upper 95\% limit} = \bar{X} + 1.96 \, (s^2/n)^{\frac{1}{2}}$$

and

$$\text{Lower 95\% limit} = \bar{X} - 1.96 \, (s^2/n)^{\frac{1}{2}}$$

In sections 10.2.2 and 10.2.3 we calculated 95% confidence intervals for the same set of data, first based on simple random sample then by post-sampling stratification. Now we will derive the confidence limits yielded by the transformation technique in the last section (10.3.1), from which we obtained the mean of log-transformed data = $\bar{Z} = 2.20$ and the variance of log-transformed data = $s^2_{\bar{Z}} = 0.1060$. Hence, we get

$$\text{standard error S.E.}(\bar{Z}) = (s^2_{\bar{Z}}/n)^{\frac{1}{2}} = (0.1060/12)^{\frac{1}{2}} = 0.094$$

So,

$$\begin{aligned} \text{C.I.} &= \bar{Z} \pm t_{.95,(11)} \times 0.094 \\ &= 2.20 \pm 2.20 \times 0.094 \\ &= 2.20 \pm 0.2068 \end{aligned}$$

Upper 95% limit = 2.4068

Lower 95% limit = 1.9932

Transforming back on the basis of direct antilogarithms gives

retransformed mean: $\bar{X}_g$ = antilog 2.20 = 158.5

retransformed Upper limit = antilog (2.4068) = 255.2

retransformed Lower limit = antilog (1.9932) = 98.4

Clearly, the resulting confidence limits are now asymmetric about the mean as can be shown by rewriting

Upper 95% C.L. = $\bar{X}_g + 96.7\ (\bar{X}_g + 61.0\%)$

Lower 95% C.L. = $\bar{X}_g - 60.1\ (\bar{X}_g - 37.9\%)$.

The above limits can now be reconstructed, using adjusted antilogs based on the corrective formulae presented in section 10.3.1. From these formulae we obtain

adjusted mean : $\bar{X}_A$ = antilog 2.322 = 209.9

adjusted variance : $s^2_A = (182.3)^2$.

Hence, the standard error of the retransformed data is now

$$\text{S.E.}(\bar{X}_A) = (s^2_A/n)^{\frac{1}{2}} = ((182.3)^2/364)^{\frac{1}{2}} = 9.555$$

and 95% confidence interval

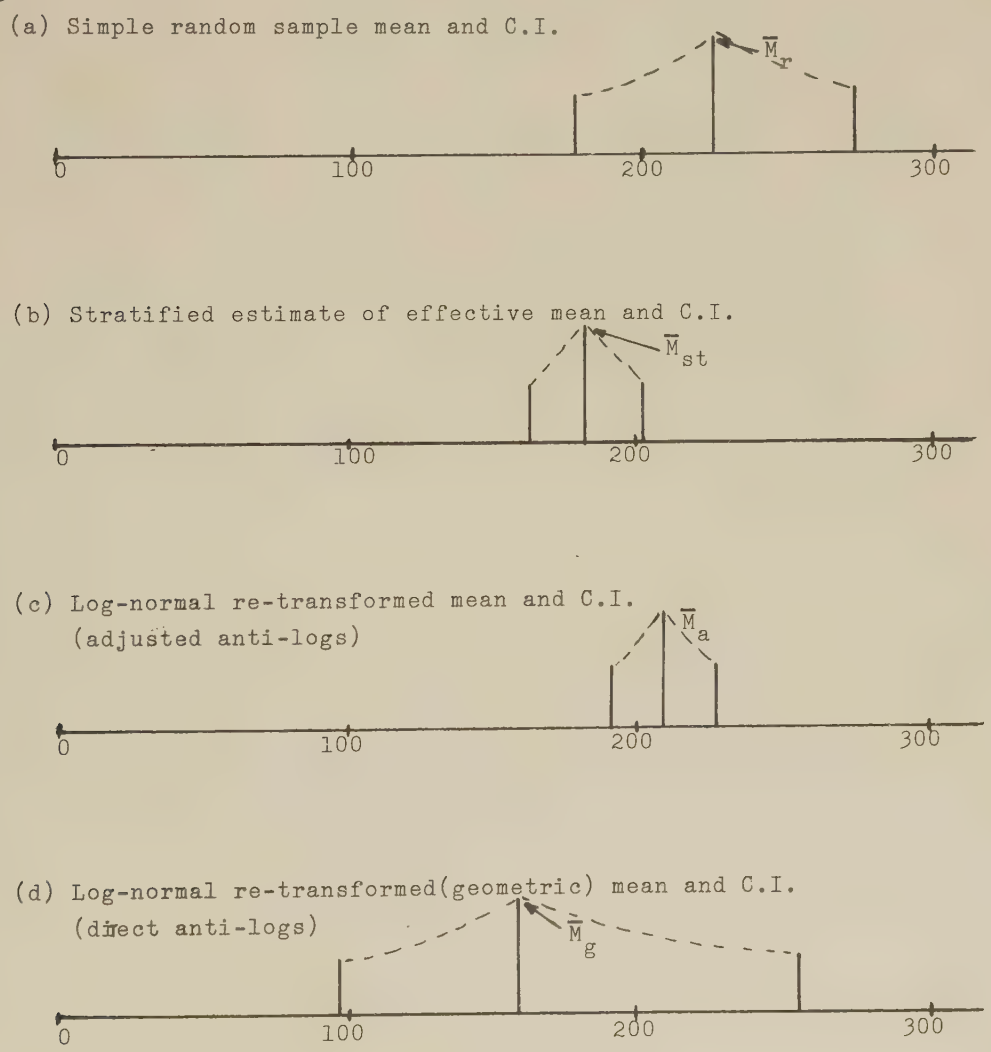
$$\begin{aligned} \text{C.I.} &= 209.0 \pm 1.96 \times 9.555 \\ &= 209.0 \pm 18.7 \end{aligned}$$

with Upper limited = 228.6 and Lower limit = 191.2.

Earlier we obtained four different estimates of means (10.3.1), and have now calculated the associated confidence intervals using four different statistical approaches. Comparison of the results is facilitated by line graphs shown in Figure 113. Visual evaluation of these graphs indicates methods (b) and (c) as the most efficient estimators for the data mean, whose two estimates differ about 13%. As for methods (a) and (d), they differ considerably among themselves both with respect to the mean and confidence intervals (the latter, d, being asymmetric) and also vary significantly to the other two methods.

Consequently, it can be concluded that for highly skewed acoustic data, the stratified or the log-transformation procedure is likely to yield the best estimates. Which one of the two methods is better, will, on one hand, depend on how uniform strata can be formed for the stratified estimation procedure, and on the other hand, on how closely the log-transformed data will fit the theoretical normal distribution in the log-normal estimation approach. To determine the exact suitability in this respect may require some detailed statistical tests that are beyond the scope of this manual.

Figure 113

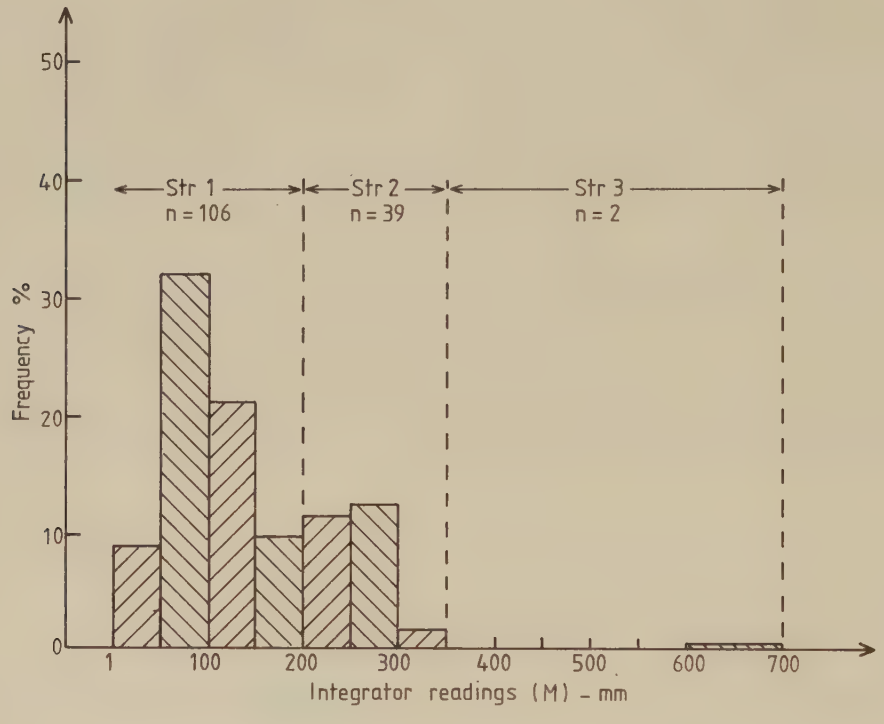


Line graphs for comparison of estimated means and 95% confidence intervals obtained from different data treatment

i) Estimates from Non-Skewed Data

So far the statistical calculation and estimates have turned around data characterized by marked positive skewness. The associated statistical problems have been demonstrated by a case study using real data from a survey of the Peruvian anchovy. We will now analyse another set of real acoustic data which is non-skewed and, intuitively, resembles a normal distribution as shown by the histogram in Figure 114. These data

Figure 114



relate to an estimation of nekton biomass in the Strait of Bali, Indonesia, from an acoustic survey by R.V. TENGGIRI from 28 February-1 March, 1982. Figure 72 shows a map of the area covered and the survey transect pattern. The integrator readings in millimetres for each 2-mile section of the cruise track (ESDU) are given in Table 14. First, we analyse the tabulated data of Table 14 in a stratified random design using the algebraic method for determination of stratum areas. Thus, we proceed as follows:

Table 14. Acoustic data observations grouped into three stratum corresponding to the frequency histogram shown in Figure 114

Stratum 1 (1-200 mm) n = 106									
Obs (No)	M (mm)	Obs (No)	M (mm)	Obs (No)	M (mm)	Obs (No)	M (mm)	Obs (No)	M (mm)
1	95	23	25	45	200	67	89	89	106
2	83	24	8	46	116	68	73	90	122
3	34	25	20	47	80	69	70	91	150
4	73	26	71	48	110	70	108	92	182
5	45	27	138	49	124	71	157	93	145
6	63	28	112	50	65	72	78	94	80
7	188	29	115	51	102	73	119	95	109
8	93	30	73	52	65	74	112	96	104
9	113	31	23	53	25	75	61	97	79
10	109	32	55	54	164	76	60	98	57
11	83	33	145	55	84	77	82	99	38
12	82	34	179	56	63	78	72	100	53
13	112	35	20	57	73	79	100	101	52
14	105	36	68	58	168	80	107	102	62
15	78	37	99	59	200	81	135	103	82
16	69	38	186	60	101	82	154	104	106
17	67	39	59	61	92	83	90	105	99
18	62	40	152	62	52	84	74	106	65
19	76	41	133	63	114	85	54		
20	100	42	140	64	147	86	36		
21	42	43	165	65	149	87	46		
22	68	44	197	66	129	88	71		
Stratum 2 (201-350 mm) n = 39									
1	211	17	316	33	208				
2	223	18	296	34	310				
3	246	19	230	35	205				
4	300	20	270	36	246				
5	243	21	284	37	290				
6	285	22	223	38	280				
7	248	23	291	39	259				
8	201	24	261						
9	234	25	258						
10	258	26	202						
11	243	27	220						
12	233	28	254						
13	210	29	282						
14	263	30	322						
15	263	31	280						
16	265	32	267						
Stratum 3 (351-700 mm) n = 2									
1	670								
2	635								

Table 15 Estimation of biomass by cluster sampling

$\sum$ Transect (t_i)																								Total
t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12	t13	t14	t15	t16	t17	t18	t19	t20	t21	t22	t23	t24	t25	
95	63	83	62	20	145	152	248	80	263	124	296	102	25	73	258	52	280	70	157	82	280	46	80	52	
83	188	82	76	71	179	246	201	110	263	265	230	65	284	168	200	635	267	108	78	72	154	71	109	62	
34	93	112	100	138	20	300	165	233	670	316	65	270	164	223	202	114	208	310	119	100	90	106	104	82	
73	113	105	42	112	68	243	197	210	–	–	–	–	84	291	220	147	149	205	112	107	74	122	79	106	
45	109	78	68	115	99	133	200	–	–	–	–	–	63	261	101	254	129	246	61	135	54	150	57	99	
–	–	69	25	73	211	140	234	–	–	–	–	–	–	–	92	282	89	–	60	290	36	182	38	65	
–	–	67	8	23	186	285	258	–	–	–	–	–	–	–	–	322	73	–	–	–	–	145	53	259	
–	–	–	–	55	223	–	243	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	
–	–	–	–	–	59	–	116	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	
n_i 5	5	7	7	8	9	7	9	4	3	3	3	3	5	5	6	7	7	5	6	6	6	7	7	7	147
Di 330	556	596	381	607	1190	1499	1862	633	1196	705	591	437	620	1016	1073	1806	1195	939	587	786	688	822	520	725	21360
Dc 66.0	111.2	85.14	54.43	75.88	132.22	214.14	206.89	158.25	398.67	235.0	197.0	145.7	124.0	203.2	178.8	258.0	170.7	187.8	97.83	131.0	114.7	117.4	74.24	103.6	145.3

Table 16 Summary of essential Data and step-by-step Calculations for Estimation of Inter-transect Correlation Coefficients based on the Data given in Table 15

Obs.	$D_{k=0}$	$D_{k=1}$	$D_{k=2}$	$D_{k=3}$	$D_{k=4}$	$D_{k=5}$	$(D_0-\bar{D})(D_1-\bar{D})$	$(D_0-\bar{D})(D_2-\bar{D})$	$(D_0-\bar{D})(D_3-\bar{D})$	$(D_0-\bar{D})(D_4-\bar{D})$	$(D_0-\bar{D})(D_5-\bar{D})$
1	330	556	596	381	607	1190	156152	135192	247852	129428	- 176064
2	556	596	381	607	1190	1499	76884	140954	73606	- 100128	- 446702
3	596	381	607	1190	1499	1862	122034	63726	- 86688	- 166410	- 260064
4	381	607	1190	1499	1862	633	116831	-158928	-305085	- 476784	104533
5	607	1190	1499	1862	633	1196	- 82992	-159315	-248976	54587	- 84474
6	1190	1499	1862	633	1196	705	216720	338688	- 74256	114912	- 50064
7	1499	1862	633	1196	705	591	650160	-142545	220590	- 96105	- 169635
8	1862	633	1196	705	591	437	- 222768	344736	-150192	- 265104	- 420336
9	633	1196	705	591	437	620	- 75582	32929	58123	92157	51714
10	1196	705	591	437	620	1016	- 50958	- 89946	-142614	- 80028	55404
11	705	591	437	620	1016	1073	39187	62878	34866	- 24138	- 32631
12	591	437	620	1016	1073	1806	109671	61542	- 42606	- 57597	- 250376
13	437	620	1016	1073	1806	1195	97578	- 67554	- 91323	- 396984	- 142197
14	620	1016	1073	1806	1195	939	- 37908	- 51246	-222768	- 79794	- 19890
15	1016	1073	1806	1195	939	587	35478	154224	55242	13770	- 43254
16	1073	1806	1195	939	587	786	208488	62403	18615	- 58473	- 14892
17	1806	1195	939	587	786	688	324632	80920	-254184	- 64736	- 158032
18	1195	939	587	786	688	822	28985	- 91047	- 23188	- 56606	- 10912
19	939	587	786	688	822	520	- 22695	- 5780	- 14110	- 2720	- 28390
20	587	786	688	822	520	725	18156	44322	8544	89178	34443
21	786	688	822	520	725	-	11288	2176	22712	8772	-
22	688	822	520	725	-	-	5312	55444	21414	-	-
23	822	520	725	-	-	-	10688	3264	-	-	-
24	520	725	-	-	-	-	43086	-	-	-	-
25	725	-	-	-	-	-	-	-	-	-	-
$\sum$	21360						1778427	817137	-894426	-1422803	-2061819

$\bar{D}$ 854.4

Stratum 1 (0-200 mm)

$n_1 = 106, \quad A_1 = (ESDU)^2 \times n_1 = 4 \times 106 = 424 \text{ mile}^2$

Let $M_i = x_i$, then we have : $\bar{x}_1 = \left(\sum_{i=1}^{n_1} x_{1_i} \right) / n_1 = 95.15$

$S_{\bar{x}_1} = 43.68$ and $S^2_{\bar{x}_1} = 1907.94$

$t_{.95} = 1.98$ (from Student's t-tables)

$C.I. = \bar{x}_1 \pm t_{.95} (S^2_{\bar{x}_1} / n_1)^{\frac{1}{2}} = 95.15 \pm 1.98 (18.0)^{\frac{1}{2}}$

$= 95.15 \pm 8.4$

Stratum 2 (201-350 mm)

$n_2 = 39, \; A_2 = (ESDU)^2 \cdot n_2 = 4 \times 39 = 156 \text{ mile}^2$

$\bar{x}_2 = \left(\sum_{i=1}^{N_2} x_{2_i} \right) / n_2 = 255.87$

$S_{\bar{x}_2} = 33.07$ and $S^2_{\bar{x}_2} = 1093.6$

$C.I. = \bar{x}_2 \pm t_{.95} (S^2_{\bar{x}_2} / n_2)^{\frac{1}{2}} = 255.9 \pm 2.02 (28.04)^{\frac{1}{2}}$

$= 255.9 \pm 10.7$

Stratum 3 (351-700 mm)

$n_3 = 2, \quad A_3 = (ESDU)^2 \cdot n_3 = 4 \times 2 = 8 \text{ mile}^2$

$\bar{x}_3 = \left(\sum_{i=1}^{n_3} x_{3_i} \right) / n_3 = 652.5$

$S_{\bar{x}_3} = 24.75$ and $S^2_{\bar{x}_3} = 612.56$

$$C.I. = \bar{x}_3 \pm t_{.95} \times (S^2_{\bar{x}_3}/n_3)^{\frac{1}{2}} = 652.5 \pm 12.7 \times (306.28)^{\frac{1}{2}}$$

$$= 652.5 \pm 222.3$$

Combining the above results to find the stratified variance (V_{st}) we obtain

$$V_{st}(\bar{x}) = \sum_{j=1}^{3} V(\bar{x}_j) A_j^2 = 18 \times 424^2 + 28 \times 156^2 + 306.2 \times 8^2 = 3,937,049.6$$

and the standard error: $S.E. = (V_{st}(\bar{x}))^{\frac{1}{2}} = (3937049.6)^{\frac{1}{2}} = 1984.2$

Effective stratified mean:

$$\bar{x}_{st} = (\bar{x}_1 n_1 + \bar{x}_2 n_2 + \bar{x}_3 n_3)/(n_1 + n_2 + n_3)$$

$$= (95.15 \times 106 + 255.87 \times 39 + 852.5 \times 2)/(106 + 39 + 2)$$

$$= 145.37$$

At this point it will be noted that the relevant confidence limits should be established in terms of echo-abundance (E = product of integrator value times area) because the stratified standard error now represents an area-weighted quantity. Since, however, the biomass weight is given by the product of the echo-abundance and scaling factor ($W_B = EC$), the confidence intervals can also be established for the mean biomass estimate. The pertinent scaling factor was: C = 0.54 tonnes/mile^2 per mm integrator deflection. Hence mean biomass estimate (i.e. point estimate)

$$\bar{W}_B = \bar{x}_{st} \times C \times (A_1 + A_2 + A_3) = 145.37 \times 0.54 \times (424 + 156 + 8)$$

$$= 46,157.9 \text{ (tonnes)}$$

$$C.I. = \bar{W}_b \pm C\, t_{.95,df} (V_{st}(\bar{x}))^{\frac{1}{2}} = \bar{W}_b \pm 0.54 \times 1.98^* \times 1984.2$$

$$= 46,158 \pm 2,121 \text{ (tonnes)}$$

---

* for df = $(n_1 + 1) + (n_2 + 1) + (n_3 + 1) = 144$

giving Upper 95% C.L. = 48,279 and Lower 95% C.L. = 44,037
Resulting in percentage bounds of ± 4.6%

Our interest now is to re-analyse the same data in a simple random design for comparison with the above result.

ii) Simple random sample

With a scientific pocket calculator we obtain:

$n = 147$, $A = 588$ n.mile^2 $\bar{x} = 145.38$, $S_{\bar{x}} = 101.38$

$$S.E. = (S^2_{\bar{x}}/n) = ((101.38)^2/147)^{\frac{1}{2}} = 8.36$$

and $t_{.95} = 1.98$ as before.

$$C.I. = \bar{W}_B \pm t_{.95} \times C \times A \times (S.E.) = 145.38 \times 0.54 \times 588 \times 8.36$$

$$= 46,161 \pm 5,256$$

now giving Upper 95% C.L. = 51,470 and Lower 95% C.L. = 40,905
corresponding to percentage bounds of ± 11.4%.

Comparison of the stratified/non-stratified results, in relation to virtually non-skewed data, brings out the following points

(a) Both methods give almost exactly the same estimates for the data mean, thus the simple random estimator, in this case, can be considered unbiased.

(b) The stratified estimator is more efficient since it gives considerably narrower confidence intervals (i.e. 4.6% compared with 11.4%) and hence, more precise estimates.

It will be noted that in the foregoing procedure and calculation of confidence intervals, only one variable has been considered, namely the integrator observation (M_i), alternatively denoted by x_i for convenience. Recalling that 'M' is proportional to the product of fish density times back-scattering coefficient, i.e.

$$M \propto \rho_v \times (\sigma/4\pi)$$

it is clear that M contains components of variability related firstly to natural variations in fish density (behaviour) and, secondly, to variations in the reflectivity property of the fish which in turn depends on the fish size and spatial orientation pattern. In addition, it includes a certain component of variability associated with the measurement system itself. Consequently, the size of the confidence intervals are governed largely by uncontrolled variations directly related to the structure and dynamics of the natural population, but not so much attributed to the variability in the acoustic measurement method itself. To separate the latter component from the intrinsic

variability in the population is obviously a difficult task. Theoretically it might be approached on the basis of experimental, replicate survey designs and assumptions of constant population size in a given area. Such an approach would require rare experimental conditions coupled with detailed analysis of variance of the results.

A different practical approach to the construction of in-situ confidence intervals was devised by Lozow (1973), where intervals at a given confidence level can be constructed as a function of the relative level of variability between ρ_v and $(\sigma/4\pi)$. The interested reader is advised to study Lozow's paper. Further discussion of the subject is beyond the scope of this manual.

iii) Confidence intervals vs. serial correlation

In the previous calculations, the assumption was made that the individual observations, M, represented statistically independent samples, implying that although the samples are normally obtained in a serial manner, they are expected to be free of serial correlation effects. However, several workers have shown that this assumption may not be valid. Bazigos (1976) estimated auto-correlation coefficients for different density strata of acoustic data obtained during an integrator survey of Lake Tanganyika in November 1973 pointing out that this would have inflationary effects upon the variance but did not suggest a correction. Nickerson and Dowd (1977) describing estimates of fish density realized that successive acoustic observations could be significantly correlated and thus result in an underestimate of the actual variance. To correct for this they used a model given by Hogg and Craig (1968).

$$S^2 = S_a^2 (1 + 2 \sum P_j)$$

where S_a^2 = variance estimate of the serial observations
$= \sum (x_i - \bar{x})^2/(n - 1)$, and
P_j = autocorrelation coefficient between a pair of observations j apart, $1 \leq j \leq n - 2$

Shotton and Dowd (1975) examined the problem of variance estimation for acoustic data and suggested the use of a cluster sampling estimate of Hanse et al. (1953). Also, Williamson (1982) presented results from a computer simulation study designed to examine the effect of auto-correlation on the variance of the random sample estimate of μ_d and to evaluate the use of cluster sampling approach for estimating μ_d.

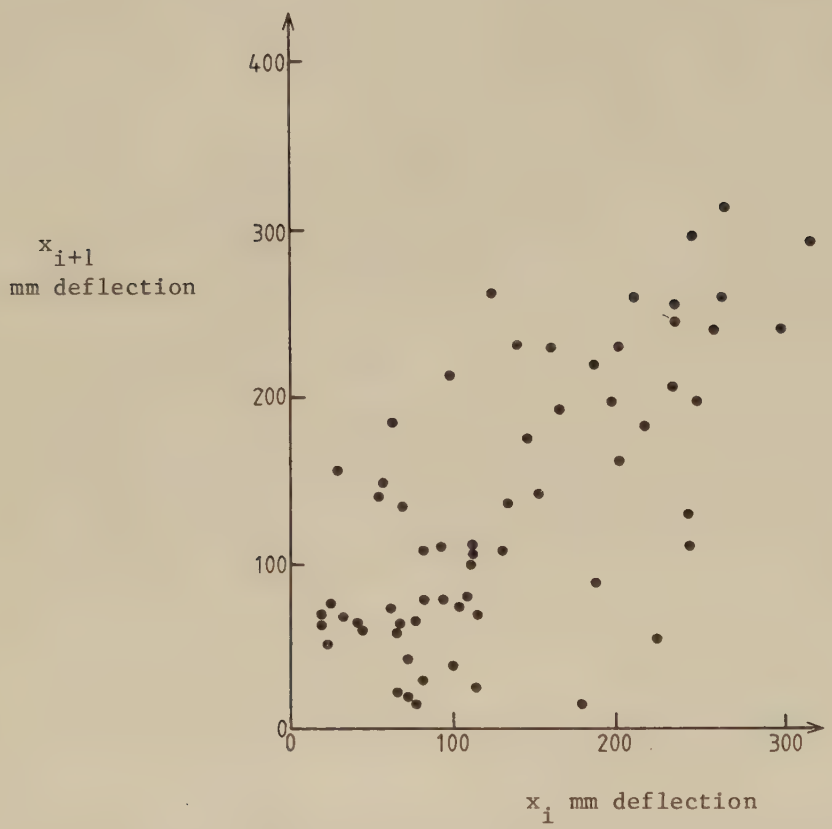
Further theoretical background will not be discussed in this manual, but in order to illustrate the importance of the serial correlation effects, we will now re-analyse the previous data (Table 14); using formulae from Williamson (1982).

iv) Analyses of data in a cluster design

The previous analysis assumed no serial correlation or this source of variance was omitted. Estimated variance and the associated bounds on the point estimate are therefore underestimates depending upon the extent of serial correlation. This was explored by two scatter diagrams of the observations viz. x_i versus x_{i+1} (Figure 115), x_i versus

x_{i+2} (Figure 116). While there is a high degree of correlation between one observation

Figure 115



and the next adjacent one x_{i+1}, this correlation disappears between x_i and x_{i+2}. In other words the auto-correlation function $r(k) = 0$ for $\log k = 2$. This fact must therefore be incorporated in the variance estimate for the mean density $\bar{d}$ in the surveyed area. An approximate expression from Williamson (1982) is:

$$\text{Var}(\bar{d}) \approx \frac{1}{N^2} \frac{t}{t-1} \left[\sum_{i=1}^{t} D_i^2 + \bar{d}^2 \sum_{i=1}^{t} n_i^2 - 2\bar{d} \sum_{i=1}^{t} D_i n_i \right]$$

Here t = total number of transects

n_i = number of observations within a transect i

N = total number of observations or $\sum_i n_i$

D_i = sum of n_i observations in transect i

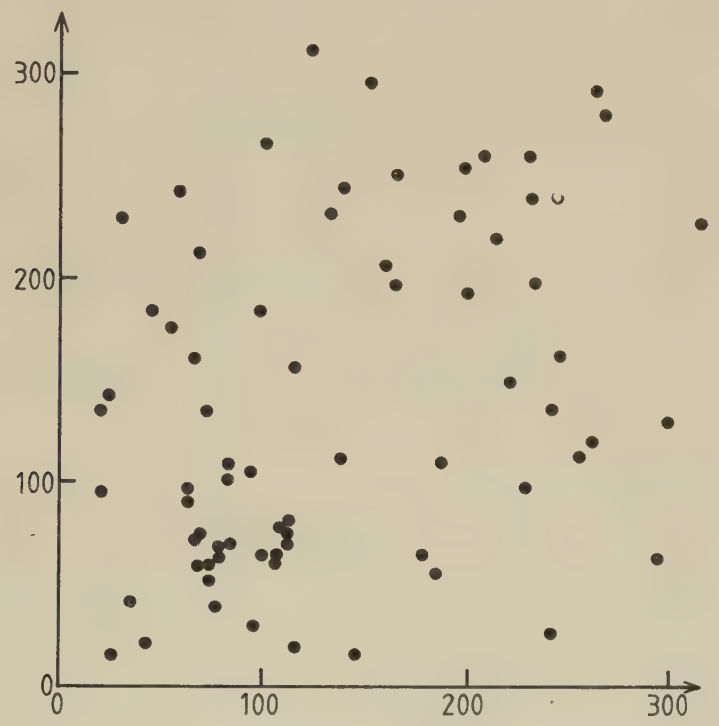
These data are summarized in Table 15; 25 transects (clusters) are listed derived by adding the short connecting transect to the preceding long one perpendicular to the coast line.

The given variance estimate is an approximation but a rather good one when the coefficient of variation (CV) of $\bar{n}$ is < 0.2

$$\frac{(\mathrm{Var}\ (\bar{n}))^{\frac{1}{2}}}{\bar{n}} = \left[\frac{\sum n_i^2 - \frac{(\sum n_i)^2}{t}}{t\ (t-1)} \right]^{\frac{1}{2}} / \frac{\sum n_i}{t} < 0.2$$

By using the data in Table 15 the calculated value became CV = .06 or well within the given limit.

Figure 116



By substitution of the values in Table 15 we obtain the necessary auxiliary quantities for substitution in the formulae for variance

$$\bar{d} = \sum D_i / \sum n_i = 21360/147 = 145.31$$

$$\sum n_i^2 = 939$$

$$\sum D_i n_i = 129,553$$

$$\text{Var}(\bar{d}) = (1/147^2)\ (25/24)\ \{22,222,511 + 145.32^2 \cdot 939 - (2.145.31)\ (129,553)\}$$
$$= (1/21609)\ (1.0417)\ (42,049,492 - 37,650,693)$$
$$= 212.05$$

The bounds on the point estimate, which is very close to the previously derived estimate (145.37) are in this case substantially increased.

$$\text{C.I.} = \bar{d} \pm t\ (\text{Var}(\bar{d}))^{\frac{1}{2}} = 145.03 \pm 1.98\ (212.05)^{\frac{1}{2}} = 145.03 \pm 28.83\ (\text{mm})$$

Calculation of total biomass in tonnes proceeds in the same manner as before by using the scaling factor C = 0.54 tonnes/mile^2/mm, and a total area estimate of A = 588 mile^2. Thus, total biomass

$$\bar{W}_B = \bar{d}\ C\ A = 145.31 \times 0.54 \times 588 = 46,139\ (\text{tonnes})$$

And the corresponding bounds (B)

$$B = \pm t\ (\text{Var}(\bar{d}))^{\frac{1}{2}} \times C \times A = \pm 1.98 \times 14.56 \times 0.54 \times 588 \simeq 9,154$$

giving Upper 95% C.L. = 55.293 (48,279*) and Lower 95% C.L. = 36,985 (44,037*)

resulting in percentage bounds of ± 19.8%.

* from the stratified estimate

The important point brought out by these two principally different ways of computing the variance, is the substantial impact serial correlation has on the magnitude of the variance around the mean density. In fact it has more than trebled. This consists of both intra- and inter-transect serial correlation. The reality of the latter one is in this case explored by computing the correlation coefficient between D_i and D_{i+k} where k = 1, 2, 3, ... etc., is the lag in number of observations between paired observations, e.g. D_i and D_{i+3} when k = 3.

Thus, the auto-correlation coefficient r_k measures the correlation between integrator readings k observations apart. The closer r_k is to 1, the higher the degree of serial correlation in the sample. To the contrary, values of r_k close to zero indicate little or no serial correlation in the sample.

The correlation coefficient for the intertransect (or inter-cluster) correlation, up to the 5th order was estimated from the approximate formula

$$r_k = \sum_{i=1}^{t-k} (D_i - \bar{D})\ (D_{i+k} - \bar{D})\ (t)\ /\ (t-k)\ (t-1)\ S_{\bar{D}}^2$$

The basic data for this formula are summarized in Table 16. By calculator

$\bar{D}_i = 854.4 \simeq 854$ and $\hat{S}^2_{\bar{D}} = (412.42)^2 = 170{,}090$

Using this result and the tabulated data we obtain

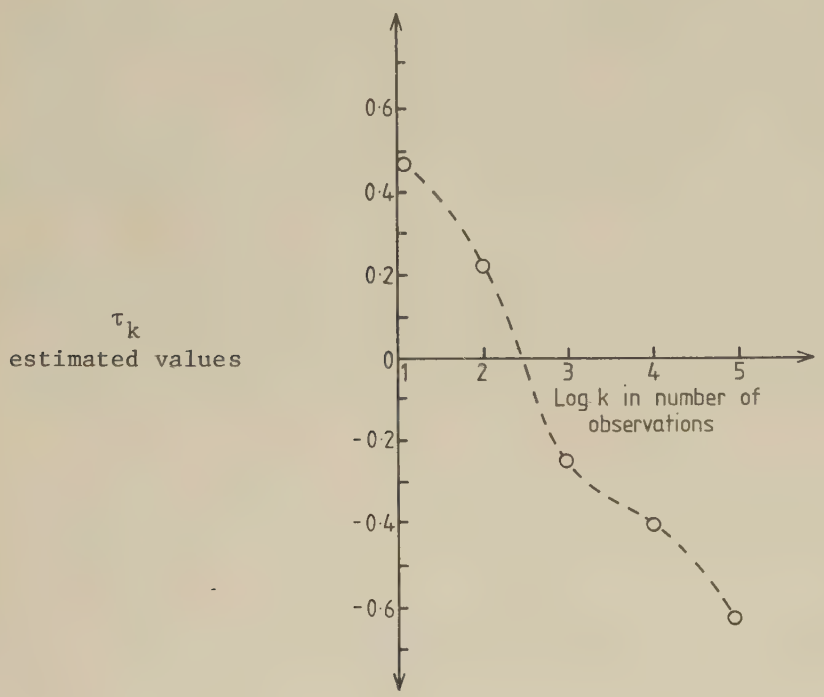
$r_{k=1} = (1{,}778{,}427 \times 25) / 24 \times 24 \times 170{,}090 = 0.456$

Repeating the calculation we can summarize the following results

$r_{k=1} = + 0.456$
$r_{k=2} = + 0.218$
$r_{k=3} = - 0.249$
$r_{k=4} = - 0.415$
$r_{k=5} = - 0.631$

these are presented graphically in a correlogram (Figure 117).

Figure 117



The fact that two closely spaced transects (= 1 ESDU in this case) show a positive correlation is expected intuitively since the serially returned observations (cluster returns) come from a fish population where natural forces are likely to induce a slow change, or even a trend, as we proceed from one transect to the next one, or from one ESDU to the following one. As a result, auto-correlation effects in acoustic survey samples may dictate the need to introduce a correction in the variance expression and this may significantly increase the estimated confidence intervals. As for the specific type of correction to be used, it is a subject under study by some writers and therefore difficult, at present, to define or recommend any optimum approach to the problem. However, it is noteworthy that Shotton and Dowd (1975) concluded that of the three

methods they examined, only the cluster estimate of Hansen, Hurowitz and Madow (1953) appeared conceptually sound with respect to assumptions of the data.

10.3.3 Allocation of Survey Samples

If there is some knowledge of the expected nature of the overall variance, for example when planning a second survey in a given area, and if little change is expected in the nature of the sampling results, then the variance can be decreased by improving the allocation of sampling effort. Transects of greater length are preferred when the intra-transect correlation is high. When most of the variation occurs between transects, then more transects of shorter length would decrease the variance. If transects make parallel and complete crossings of the stratum then to this extent the transect lengths will be predetermined.

The acoustic data used for the two preceding case studies are related to systematic surveys with equidistant transect spacing. In such cases, the allocation will be proportional to the area sizes in each stratum. This section is intended to introduce the concept of 'optimum sampling allocation' and as a further development of the above case studies, to make comparisons between the proportional and optimum allocation of sampling efforts in stratified sampling.

The optimum allocation of survey effort refers to a sampling method that gives a minimum variance under the restriction (cost not considered) that the total sample size is n and that we have h strata. In this case, the number of samples per stratum, n_h, is given by

$$n_h = (n\ A_h\ S_h)/\Sigma_h\ A_h\ S_h$$

A_h = size of the stratum area

S_h = standard deviation of the stratum sample.

Applying the above formula, the calculation can proceed as follows.

1) For the Skewed Data

From Table 9 we can readily compute the standard deviation

$$\text{Stratum 1} : S_1 = (V(\bar{M}_1))^{\frac{1}{2}} = (3.7)^{\frac{1}{2}} = 1.92$$
$$\text{Stratum 2} : S_2 = (V(M_2))^{\frac{1}{2}} = (195.0)^{\frac{1}{2}} = 13.96$$
$$\text{Stratum 3} : S_3 = (V(M_3))^{\frac{1}{2}} = (174{,}315.0)^{\frac{1}{2}} = 417.5\ .$$

Further, $\Sigma\ A_h\ S_h = A_1S_1 + A_2S_2 + A_3S_3 = 9200 \cdot 1.92 + 7000 \cdot 13.96 + 300 \cdot 417.5$
$= 17{,}664 + 97{,}720 + 125{,}250 = 240{,}634.$

Having obtained the relevant numerical values for substitution in the formulae for optimum sample size by stratum, we get

$n_1 = 364 \times 17664/240634 = 26.72 \simeq 27$

$n_2 = 364 \times 97720/240634 = 147.82 \simeq 148$

$n_3 = 364 \times 125250/240634 = 189.46 \simeq 189.$

The actual sampling allocation is compared with the estimated optimum allocation

Table 17

Stratum (No.)	Sample allocation				Difference (ratio)
	Actual		Optimum		
	n	%	n	%	
1	174	47.8	27	7.4	6.5 times over-sampling
2	178	48.9	148	40.7	1.2 times over-sampling
3	12	3.3	189	51.9	15.7 times under-sampling
Totals:	364	100	364	100	

The result shows that for the given criteria, only stratum 2 was adequately sampled, while the sampling allocation in the low density stratum (1) appears exorbitant and, to the contrary, the sampling effort in the high density stratum (3) is totally insufficient. Consequently, the variance could be reduced by a proper allocation of sampling within strata.

ii) For the Non-Skewed Data

Following the same procedure as above, we obtain the following result:

Stratum 1 : $n_1 = 106$; $A_1 = 424$; $S_1 = 4.24$

Stratum 2 : $n_2 = 39$; $A_2 = 156$; $S_2 = 5.30$

Stratum 3 : $n_3 = 2$; $A_3 = 8$; $S_3 = 17.50$

Hence,

$$\Sigma A_h S_h = 424 \times 4.24 + 156 \times 5.30 + 8 \times 17.50$$
$$\simeq 1798 + 827 + 140$$
$$\simeq 2765$$

So, the optimum sampling allocation is

$n_1 = 147 \times 1798/2765 = 95.59 \simeq 96$

$n_2 = 147 \times 827/2765 = 43.97 \simeq 44$

$n_3 = 147 \times 140/2765 = 7.44 \simeq 7.$

The comparison with the actual sampling is shown in Table 18.

Table 18

Stratum (No.)	Sample allocation				Difference (ratio)
	Actual		Optimum		
	n	%	n	%	
1	106	72.1	96	65.3	1.1 times over-sampling
2	39	26.5	44	29.9	1.13 times over-sampling
3	2	1.4	7	4.8	3.5 times under-sampling
Totals:	147	100	147	100	

The result shows that for the kind of data in question, the actual allocation of the survey effort does not deviate very much from an optimum allocation, although stratum 3 appears insufficiently sampled. Hence, in this case, a change in the sampling effort is not likely to produce much reduction in the variance.

APPENDIX I

UNITS AND SYMBOLS

The International System of Units has received worldwide acceptance, so it is especially important that projects associated with the United Nations Organization should make use of this system whenever possible to ensure uniformity in its training programmes and in reporting the results of its work.

Systeme International d'Unités (International System of Units) abbreviated SI, was adopted by the 11th General Conference of Weights and Measures in 1960. It includes three classes of units:

1. Base units
2. Supplementary units
3. Derived units

which together form the coherent system of SI units.

1. Base Units: SI is founded on the seven base units below.

Quantity	Name of Base Unit	Symbol
Length	metre	m
mass	kilogram	kg
time	second	s
electrical current	ampere	A
thermodynamic temperature	kelvin	K
luminous intensity	candela	cd
amount of substance	mole	mol

2. Supplementary Units

These units have not yet been classified as either base units or derived units.

Quantity	Name	Symbol
plane angle	radian	rad
solid angle	steradian	sr.

3. Derived Units

Only those thought to be appropriate to this manual are listed below.

Quantity	Name	Symbol	Expressed as
frequency	hertz	Hz	$1Hz = 1s^{-1}$
force	newton	N	$1N = 1kg\ m/s^2$
pressure and stress	pascal	Pa	$1Pa = 1N/m^2$
work, energy, quantity of heat	joule	J	$1J = 1Nm$
power	watt	W	$1W = 1J/s$
electrical potential	volt	V	$1V = 1W/A$
electrical capacitance	farad	F	$1F = 1As/V$
electrical resistance	ohm	Ω	$1\Omega = 1V/A$
electrical conductance	siemens	S	$1S = 1\Omega^{-1}$

4. Other Units

Quantity	Name	Symbol	Expressed as
absorption	alpha	α	dB/km
efficiency	eta	η	%
angle	theta	Θ	degrees
wavelength	lambda	λ	m
density	rho	ρ	kg/m^3
wave speed		c	m/s
acoustic resistance	Rayl	ρc	kg/m^2s
acoustic cross-section	sigma	σ	m^2
duration of time	tau	τ	s
angular velocity	omega	ω	rads/s
angle (ideal beam)	Psi	Ψ	
intensity		I	
electrical power		Pe	Watts
acoustic power		WA	W
source level		SL	dB/1μPa/1m
directivity index		DI	10 log(4πarea)/λ^2
transmission loss		TL	dB
target strength		TS	dB
receiving transducer sensitivity		SRT	dB/1V/1μPa
radiation resistance		RR	ohms
voltage at transducer terminals		VRT	dB/V
echo level		EL	dB/1μPa
band level		BL	dB
calibrated voltage output		VR	dB/V

5. Multiples of SI Units

Again, only those multiples likely to occur in this manual are included:

Multiplication Factor	Name	Symbol
10^6	mega	M
10^3	kilo	k
10^2	hecto	h
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p

Examples

$1\ cm^3 = (10^{-2}m)^3 = 10^{-6}m^3$

$1\ \mu s^{-1} = (10^{-6}s)^{-1} = 10^{6}s^{-1}$

$1\ mm^2/s = (10^{-3}m)^2/s = 10^{-6}m^2/s$

compound prefixes should not be used, write nm (nanometre) NOT mμm

The choice of multiples (decimal multiple or submultiple) of an SI unit is taken for convenience, i.e. the particular multiple chosen will be the one leading to numerical values within a practical range. It is usually possible to keep these values between 0.1 and 1000.

Examples

0.00394m can be written as 3.94 mm

1401 Pa can be written as 1.401 kPa

3.1×10^{-8}s can be written as 31 ns

In calculations, errors may be avoided more easily if quantities are expressed in SI with the prefixes being replaced by powers of 10.

Symbols for units are printed in lower case up-right type and remain unaltered in the plural, they should be written without a final full stop and be placed after the complete numerical value. Upper case letters are used where the name of the unit is derived from a proper name, e.g. Newton, N or Pascal, P.

Compound units, formed by dividing one unit by another, e.g. $\frac{m}{s}$

are indicated as m/s, or ms^{-1} the latter form is preferable where multiple units occur on the same line.

6. Notes

1) The unit of pressure in older textbooks was the μbar, this has been replaced by the μPa. To convert μbar to μPa, add 100 dB,
   e.g. 110 dB/1μbar/1m = 210 dB/1μPa/1m
   or -110 dB/1V/1μbar = -210 dB/1V/1μbar.
2) Use of the nautical mile is standard for seagoing purposes, where the terms mile or $mile^2$ are used, a nautical mile is implied. (Never use nm as an abbreviation for nautical mile.
3) The prefix hydro is regarded as superfluous when fisheries acoustics are being considered. It is not used in this manual.
4) Some duplication in the use of symbols inevitably occurs but an explanation is given in the section concerned.

APPENDIX II

GLOSSARY OF TERMS

A. 1. absorption coefficient : the coefficient α, denoting the power loss due to absorption (symbol α)

2. absorption loss : a temperature and frequency dependent power loss to acoustic waves, linear with distance (symbol αR : unit dB)

3. acoustic axis : region of maximum response, normally perpendicular to the face of a transducer.

4. acoustics : the theory of acoustic waves and their propagation

5. acoustic calibration : measuring the performance of an acoustic system to a specified standard (unit dB)

6. acoustic equation : see sonar equation

7. acoustic equipment : devices for the generation or reception of acoustic waves.

8. acoustic intensity : amount of acoustic power through unit area. Reference is a plane wave intensity having an rms pressure equal to 1μPa (one micro pascal) (symbol I : unit dB/1μPa)

9. acoustic power : acoustic energy per unit time

10. acoustic speed : speed at which acoustic waves travel (symbol c; unit m/s)

11. amplification : amount by which a signal is increased, see gain (unit dB)

12. amplifier : the device which increases signal size

13. amplitude : size of a signal.

14. analogue : functional similarity: (a circuit or device to generate voltages proportional to quantities)

15. angular resolution : the amount of discrimination between targets separated in angle (unit degrees)

16. array : multi-element transducer

17. attenuation : reduction ot acoustic power due to spherical spreading and absorption of the waves (unit dB/km)

18. automatic gain control : amplification varied in proportion to a received signal to reduce output voltage variation.

B. 1. back scattering : amount of acoustic power scattered by a target into the direction of the transmitting transducer.

2. back scattering layer: biomass layer which back-scatters acoustic power.

3. band width : the amount frequencies extend on either side of the nominal acoustic frequency (symbol BW; unit Hz)

4. beam angle : full included angle between the half-power points (symbol Θ ; unit degrees)

5. beam half angle : angle where the acoustic power is half that of the axis (symbol $\Theta/2$ unit degrees)

6. beam dual : see dual beam system

7. beam equivalent : see equivalent beam

8. beam deflection : amount by which a beam is moved in angle from its normal acoustic axis.

9. beam narrow : when full angle is less than 10°.

10. beam pattern : two-dimensional pattern showing the relative response of a beam

11. beam wide : when full angle is more than 10°.

12. beam overlap : amount by which successive pings cover the same area.

13. beam width : distance across the acoustic beam at a given range. (unit : metres)

14. blocking : when receiving function is stopped by a very large signal, as in 'white line'.

15. body towed : see towed body

16. bottom lock : when the bottom signal forms a reference for echoes just above it. (also seabed lock).

17. bottom discrimination : determining the nature of the bottom.

18. bottom noise : noise generated by tidal flow.

19. bottom pulse : electrical pulse produced from bottom echo.

C. 1. calibration : measuring or adjusting the performance of a system to a specified standard.

2. calibration equipment : signal generators, hydrophones, standard targets, projectors, oscilloscopes, voltmeters, etc.

3. cavitation : production of voids in the water due to negative pressure.

4. channelling : restriction of acoustic waves by boundaries.

5. contour line : similar function to 'white line'

6. cross section : see scattering-cross section.

D. 1. dead zone : volume of the transducer beam, usually close to the seabed, where targets cannot be detected.

2. decibel : logarithmic ratio used to express relative levels of acoustic or electrical signals (unit : dB)

3. demodulation : process of extracting information from a signal.

4. depth interval : selected interval between two depths, also known as a gate (unit metres)

5. depth range : the total depth indicated on the display (unit metres)

6. depth recorder : device which indicates and records the depth of acoustic targets and the seabed.

7. detection threshold : signal power in the receiver bandwidth relative to the noise power in a 1Hz band which permits the detection of a target against specified criteria (unit : dB)

8. digital : having the circuit state of 'OFF' or 'ON'.

9. directivity index : concentrating power of a transducer related to dimensions and acoustic wavelength, expressed in logarithmic form (symbol DI : unit dB)

10. directivity pattern : diagram of the concentrating power of a transducer in terms of beam angle and relative amplitude of the lobes.

11. display unit : for the display of signals and other information relating to the echo-sounder

12. doppler effect : frequency difference (f) between the transmitted pulse (f_0) and the received echo, due to the relative speed (V in m/s) between the ship and the target in water where the acoustic velocity is c, m/s and $f = 2f_0V/c$

13. dual beam : multi-element transducer from which two concentric beams of same frequency but different beamwidths are formed.

14. dynamic range : the extent to which signals can be processed without distortion (unit dB)

E. 1. echo : an acoustic wave reflected from a target.

2. echo level : acoustic intensity at the receiving transducer (symbol : EL; unit dB)

3. echo paper dry : recording paper conductive with high voltage.

4. echo paper moist : recording paper conductive with low voltage.

5. echogram : record of a sequence of echoes.

6. echo integrator : unit to process and add the acoustic intensities from selected depth intervals.

7. echo sounder : system comprising acoustic transmitter, echo receiver and display.

8. echo sounding : finding the depth of a target by measuring the time from transmission to echo.

9. echo ranging : finding the distance to a target by measuring the time from transmission to echo.

10. echo trace : mark on a record caused by an echo.

11. electro-acoustic : process to convert electrical energy into acoustic energy.

12. electro-strictive : material which changes its dimensions under the influence of an electric field.

13. electro-acoustical efficiency : efficiency of electrical to acoustic energy conversion (symbol η ; unit : dB, or %)

14. equipment log sheet : a table of equipment readings.

15. equivalent angle : the included angle of an 'ideal' beam, calculated from actual transducer characteristics.

16. expanded dynamic range : a technique to improve the range of tones on a paper record.

17. expanded scale : display of a portion of range or depth at a size exceeding its basic scale.

F. 1. far-field : distance beyond where the initial fluctuations of intensity occur when transmitted by a transducer.

2. figure of merit : comparative performance of acoustic systems based on maximum allowable two-way transmission loss related to a target strength of 0dB (symbol : FM; unit : dB)

3. fish abundance : how many fish are in a population.

4. fish detection : location of fish by acoustic means.

5. fish target strength : ratio of the acoustic intensity I_R reflected from a fish and measured 1 m away, to the incident acoustic intensity I_i, 10 log I_R/I_i dB (symbol : TS ; unit : dB)

6. free-field : volume of water clear of boundaries.

7. frequency : number of complete cycles of an electrical or acoustic wave to pass a given point in one second (symbol : f ; unit : Hz)

8. frequency counter : a device to count the number of complete cycles to pass a given point in a given time.

9. frequency response : the extent to which a system is sensitive to a range of frequencies (unit Hz)

G. 1. gain : amount by which the amplitude (size) of a signal is increased (unit dB)

2. geometrical loss : dispersal of energy of an acoustic wave due to the spreading effect within the geometry of the beam.

3. geometrical spreading : increase in the cross section of an acoustic beam, proportional to distance squared.

4. geometric cross-section : projected area of a target in the direction of isonification.

5. geometric zone : where the relationship of wavelength λ to the dimensions of a fish enables TS to be deduced from the laws of geometric optics. λ very much less than fish length.

6. ghost echo : an echo falsely related to the depth scale.

H. 1. hydrophone : device to receive acoustic waves and convert them to electrical signals.

I. 1. impedance : ratio of generally complex quantities of pressure and particle velocity or of voltage and current at the same time and place.

2. incident intensity : acoustic intensity falling on a target.

3. insonify : to 'illuminate' by means of acoustic waves.

4. isotropic : having non-directional properties.

5. integrator : see echo integrator.

6. intensity : see acoustic intensity (symbol I; unit dB/μPa)

7. interface : the matching unit between one instrument and another.

8. interference : an unwanted signal or a malfunction.

L. 1. layer : see scattering

2. live fish calibration : overall calibration of an echo-sounder/echo-integrator system by insonifying captive fish and measuring the received intensity

3. lobe : see side lobe

4. log sheet : see survey equipment

M. 1. manual : hand control

2. magneto-strictive : material which changes its dimensions under the influence of a magnetic field.

3. marker button : a press button to make a line on a paper record.

4. minimum recordable signal : smallest amplitude (size) of signal which can be seen on the display.

5. modulation : the process of impressing information on a signal (e.g. pulse)

N. 1. nautical mile marker : signal from ships log to mark a record, or to zero an integrator.

2. near field : the distance within which transducer measurements should not be made.

3. noise level : number of dB by which noise is above or below a given reference.

4. noise limited : distance at which detection is no longer possible because the signal is obscured by noise.

5. noise reduction : number of dB by which noise is reduced from a reference.

6. noise spectrum level : noise power for one cycle of energy, (symbol : SPL ; unit : dB/1μPa/Hz)

O. 1. oscillation : an uncontrollable state of an amplifier, or the result of an oscillatory state.

2. oscillator : electronic circuit for generating controlled oscillations.

3. oscilloscope : an instrument for viewing and measuring oscillations or signals.

P. 1. performance test : measurements to establish the standard to which a system is working.

2. ping : a name for the transmitted acoustic pulse.

3. power consumption : electrical power needed to operate acoustic equipment (unit Watts or kilo Watts)

4. phase : the time relationship of one wave to another (symbol ϕ : unit degrees)

5. pre-amplifier : boosts signals before the main amplifier.

6. projector : transmitter of acoustic power.

7. propagation : transmission and travel of acoustic waves through a medium.

8. pulse duration : the time for which a pulse continues (symbol : τ ; unit : ms).

9. pulse length : the distance a pulse extends (unit metres)

10. pulse rate : number of pulses in a given time.

11. pulse volume : the volume contained within the included angle of the beam for the extent of one pulse length at a given range (unit m^3)

R. 1. range : distance to a target (symbol : R; unit : m).

2. range resolution : the minimum distance between targets which allows them to be separated from each other (symbol : $c\tau/2$; unit : m)

3. Rayleigh scattering zone : where fish scattering cross-section varies inversely with the fourth power of wavelength, fish length much greater than λ.

4. receiving voltage response : number of dB relative to 1 Volt for a given acoustic pressure at the transducer face (symbol : VRT ; unit : dB/V)

5. reciprocity : exhibited by mutually interchangeable transducers.

6. resonance : when a circuit, or a target, is excited to different modes of vibration by a particular frequency.

7. resonant frequency : the natural frequency of operation for a transducer or circuit (symbol f : unit Hz)

8. reverberation : the sum of all scattered acoustic energy.

9. root mean square : the square root of the averaged sum of all squared values of a waveform (symbol rms)

S. 1. sampling cross-section : area across the beam at a given range (unit m^2)

2. sampling volume : selected volume within the acoustic beam.

3. source level : ratio of acoustic intensity on the axis of a source at 1 m, to a plane wave of rms pressure 1μPa (symbol : SL; unit : dB/1μPa/m).

4. scattering layer : extensive horizontal distribution of acoustic targets.

5. secondary echo : when the echo from a target or seabed is reflected back from the surface and causes a second echo from the target or seabed to be received.

6. sensitivity : degree of response to an acoustic or electrical signal.

7. shadowing : the effect caused by one target lying in the 'shadow' of another.

8. signal generator : instrument which produces electrical signals at controlled frequencies and amplitudes.

9. signal strength : intensity of an acoustic wave or amplitude of an electrical wave.

10. signal-to-noise ratio : amount by which a signal exceeds noise, or is below noise (symbol : SNR; unit : dB).

11. side lobes : all beams of a transducer except the main beam.

12. sonar : all SOund NAvigation and Ranging systems but usually reserved for near horizontally directed beams.

13. sonar equation : the equalities from which the performance of an acoustic system can be calculated. (units in dB) Now called acoustic equation.

14. speed of acoustic waves : see acoustic speed

15. standard target : a target possessing a known target strength, used for the calibration of acoustic systems (unit dB)

16. stylus : the writing tip, or tips in a paper recorder.

17. survey log sheet : table of data relating to survey readings.

18. synchronisation : the keeping together in time of recorders: units comprising an echo-sounder, a sonar, or electrical waveforms.

T. 1. target strength : ratio of the echo intensity at 1 m from a target to the incident intensity (symbol : TS ; unit : dB).

2. thermal noise : the ultimate limit to detection due to molecular activity, mainly evident above 100 kHz.

3. thermocline : temperature discontinuity where organisms often collect, thus making it acoustically 'visible'.

4. threshold : a chosen signal level below which no signals are processed.

5. timebase : the time reference to which signals on a paper recorder, or an oscilloscope, are displayed.

6. time-varied-gain : accurately controlled amplification (gain) relative to time after the transmission, used to correct for transmission loss (symbol TVG)

7. towed-body : hydrodynamically shaped body into which a transducer may be fitted.

8. transducer : device for the conversion of acoustic energy into electrical energy and vice-versa: see hydrophones, projectors, electrostrictive and magnetostrictive.

9. transceiver : combined transmitter and receiver of an echo-sounder.

10. transmission locked : display of signals related to time of transmission.

11. transistor : electronic device which amplifies, switches and oscillates in electronic circuits as required.

12. transmission loss : sum of absorption loss and geometric loss (symbol TL, unit dB)

13. transmitter : unit which produces electrical power at the required frequency.

14. trigger contact : switch to initiate transmission, or to start some function.

15. trigger pulse : electrical signal which initiates a circuit action.

V. 1. voltmeter : device for the measurement of voltages, either arising from direct or alternating current.

W. 1. wavelength : distance between the crests or the troughs of a sinewave (symbol : λ ; unit : m).

2. white line : effect of a circuit which cuts off the seabed echo recording shortly after it appears, then allows it to resume after a fixed period.

APPENDIX III

REFERENCES AND RECOMMENDED READING

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